Spatial Analysis Needs for Marine Ecosystem Management: Habitat Characterization, Spatio-temporal Models and Connectivity Analysis Frameworks

Patrick N. Halpin
Director, Geospatial Analysis Program
Nicholas School of the Environment and Earth Sciences, Duke University

Abstract

Ecosystem management in the marine environment is an especially challenging endeavor due to the enormity of marine management areas, relative sparseness of marine observation data and the highly dynamic nature of the ocean environment. Strategic development of new spatial analysis tools is needed to provide a more robust framework for analysis in this challenging environment. In this overview, I present three areas of scientific needs and example tools now under development to meet these needs. The three general areas of interest are: habitat characterization, spatio-temporal models and connectivity analysis frameworks. To address issues of habitat characterization, I present examples of benthic complexity model development as a surrogate spatial data analysis when habitat observation data is unavailable. In the second example I provide examples of the development and tuning of spatio-temporal habitat models in dynamic marine environments. In the third example, I provide examples of connectivity models, using network analysis in marine planning applications. These example applications are provided to illustrate the range of different spatial analysis tools that will be required to meet future needs for marine ecosystem scientists and managers.

Spatial analysis needs for marine ecosystem management: Habitat characterization, spatio-temporal models, & connectivity analysis

Pat Halpin
Director
Geospatial Analysis Program

NICHOLAS SCHOOL OF THE
ENVIRONMENT AND EARTH SCIENCES
DUKE UNIVERSITY

Science Needs

Charge to the speakers…

The Science Needs session will survey the spatial analyses or tools that living marine resource scientists need to understand individual components of an ecosystem and how those components interact.

Topics of discussion may include but are not limited to delineation of ecosystem boundaries, ***characterizing species distribution*** and abundance, spatial variation in food webs, ecosystem ***model choice*** and spatial data or analysis requirements, ***analytical framework*** development etc.

Science needs

- ✓ **Background**

- ✓ **Habitat characterization**
  - ✓ Benthic “habitat”
  - ✓ Pelagic “habitat”

- ✓ **Spatio-temporal modeling**
  - ✓ Habitat modeling
  - ✓ Model evaluation
  - ✓ Spatio-temporal analysis

- ✓ **Connectivity analysis framework**

Ongoing marine spatial projects:

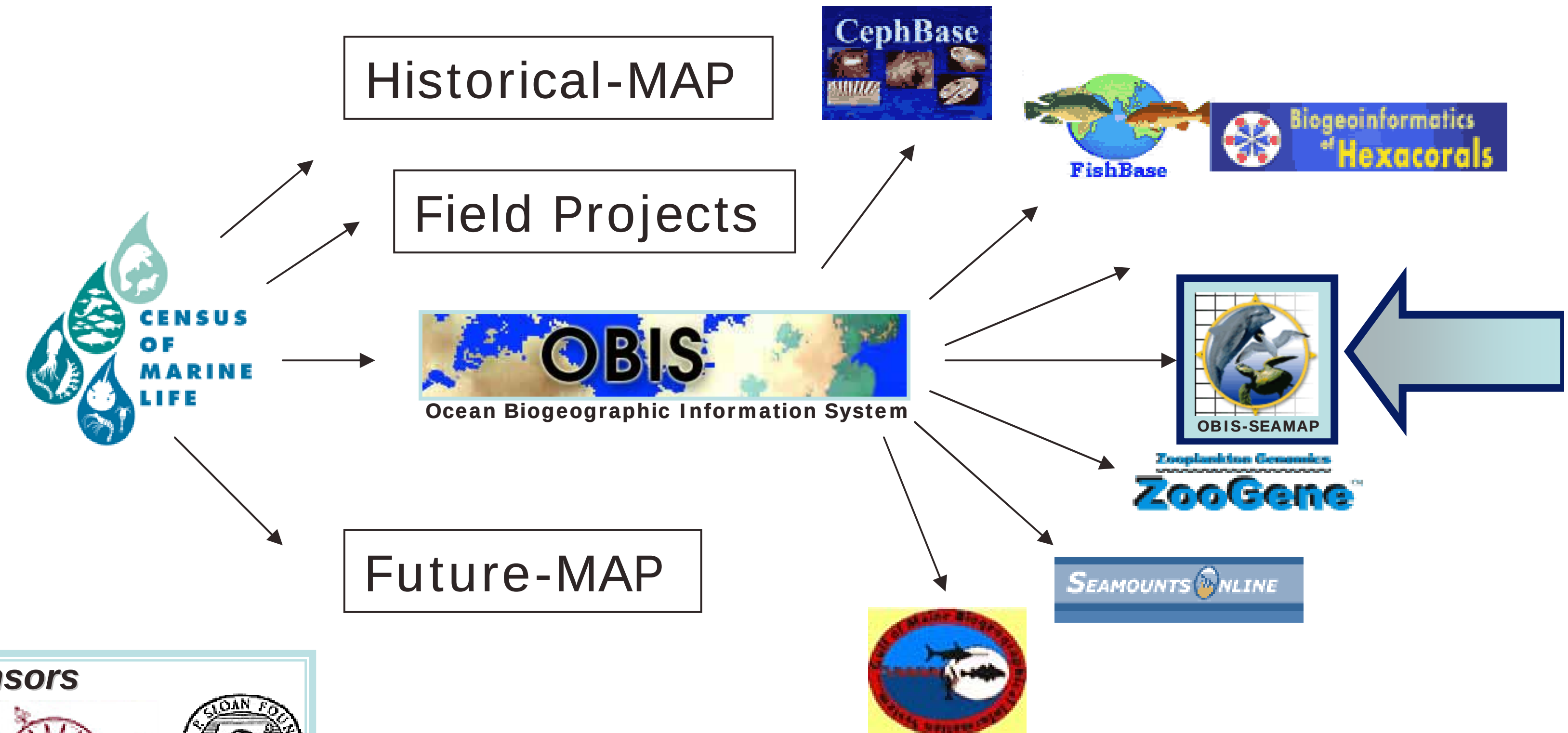
OBIS – SEAMAP

Marine mammal habitat modeling

Carolinian marine ecoregional plan
S-Central Fla. marine ecoregional plan

ESRI Marine Data Model

Ocean Biogeographic Information System - Spatial Ecological Analysis of Megavertebrate Animal Populations



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ONR Science & Technology · NOPP · Alfred P. Sloan Foundation 1934

September 8, 2004

64 datasets - **280,243** records (1947 – 2004)

Browse Datasets

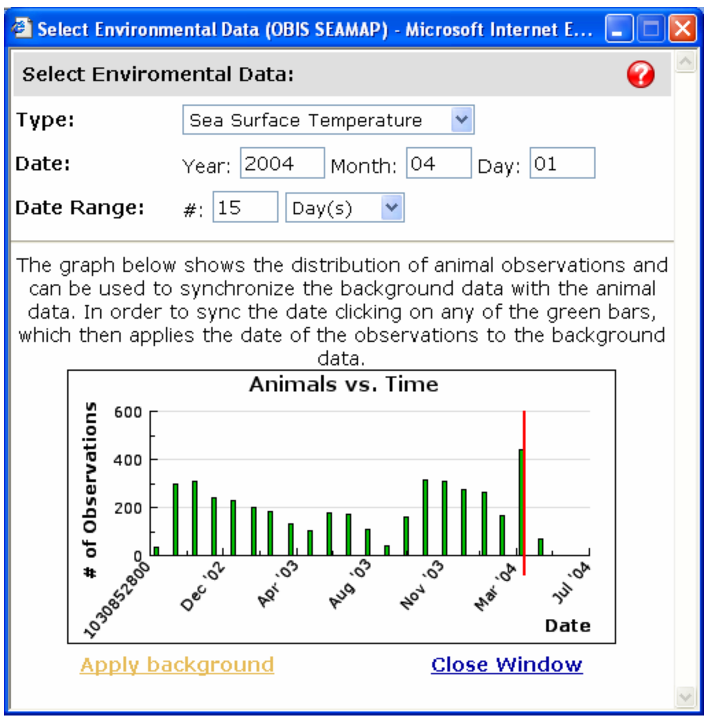
tip: column headings are sortable

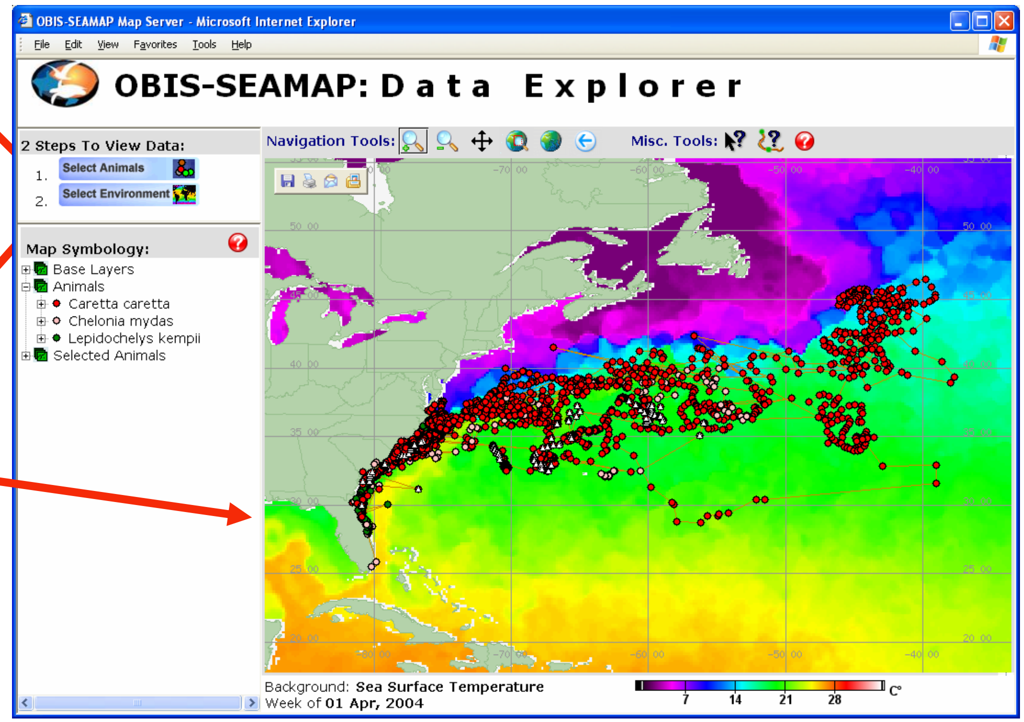
title	map	begin (years)	end (years)	birds	mammals	turtles
Allied Whale / College of Atlantic North Atlantic Humpback Whale Catalog, 1976 - 2000, ver1		1976	2000	0	3	0
Allied Whale North Atlantic Finback Whale Catalogue		1977	1991	0	648	0
BIOMASS		1980	1985	16707	0	0
Cascadia Research Blue Whale Photo IDs for US West Coast, 1972-2002		1979	2002	0	5481	0
Cascadia Research Marine Mammal Surveys in US West Coast, 2002		2002	2002	0	1220	0
Duke Marine Lab Albatross Tagging, 1997-1999		1997	1999	657	0	0
Duke North Atlantic Harbor Porpoise Tracking		1995	2000	0	5938	0
Duke North Atlantic Turtle Tracking		2002	2004	0	0	3383
IPHC Opportunistic Short-tailed Albatross		1998	2002	141	0	0
MMS aerial surveys for seabirds and mammals, Oregon and Washington		1989	1990	13872	2554	6
MMS Central/Northern California High-altitude mammals		1980	1983	0	2027	6
MMS Central/Northern California Low-altitude birds and mammals		1980	1983	16214	2725	7
MMS high altitude survey for mammals, Southern California		1975	1978	0	825	0
MMS low-altitude survey for mammals, Southern California		1975	1978	0	1006	0

Tools for Data Integration

Select Environmental Background:

- ❑ Sea Surface Temperature
- ❑ Sea Surface Height
- ❑ Wind Speed and Direction





A histogram of observations over time allows you to step through the environmental background data, retrieved on-the-fly from JPL PO-DAAC servers.

Physical Oceanography DAAC
Distributed Active Archive Center
JET PROPULSION LABORATORY

CENSUS OF MARINE LIFE

Marine Animal Data…

Ocean Biogeographic Information System

Hierarchical Information networks….

"trophic" information networks

fisheries / mgmt

top predators

prey

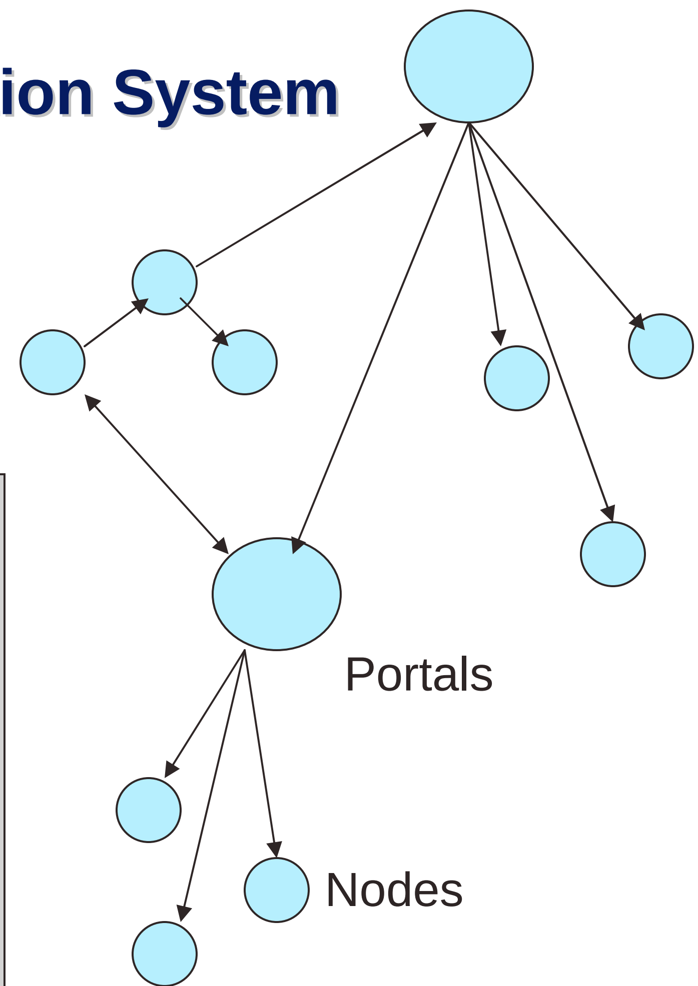
producers

oceanography

OBIS-SEAMAP

CephBase

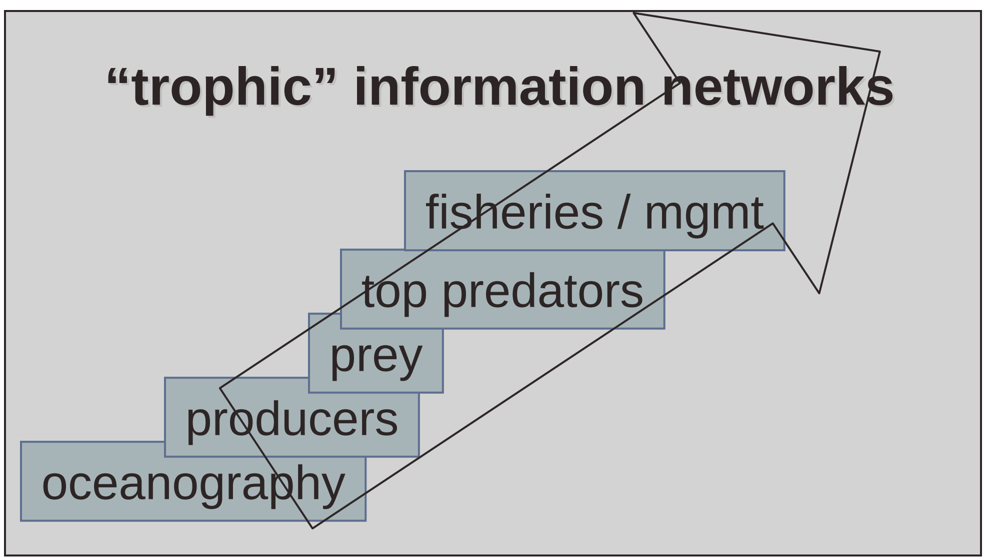
FishNet

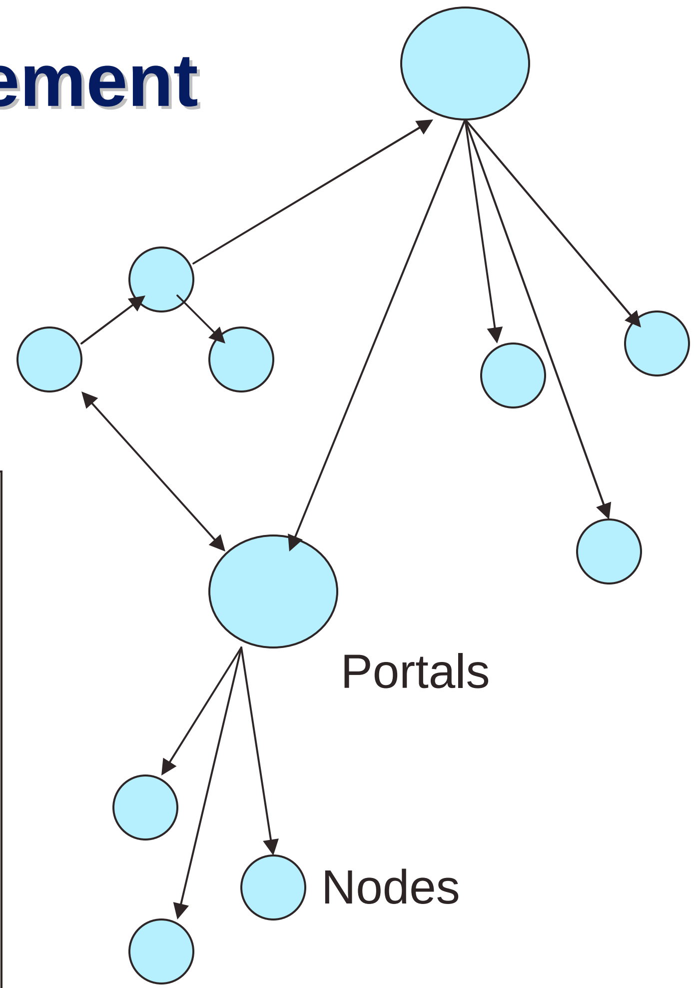


A distributed data & analysis approach

Marine ecosystem management information systems

Hierarchical Information networks….





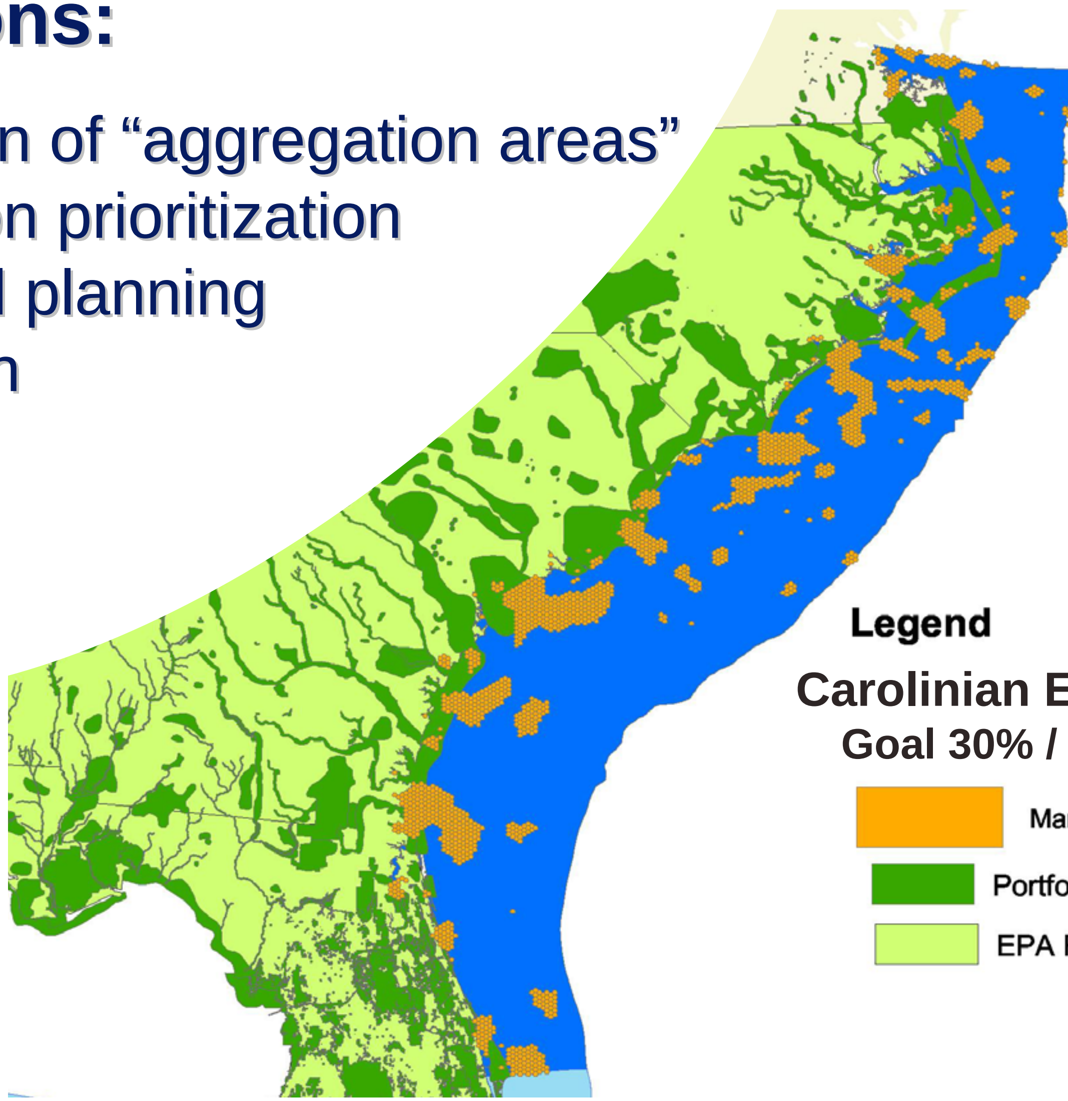
Science needs

- ✓ **Background**
- ✓ **Habitat characterization**
  - ✓ Benthic “habitat”
  - ✓ Pelagic “habitat”
- ✓ **Spatio-temporal modeling**
  - ✓ Habitat modeling
  - ✓ Model evaluation
  - ✓ Spatio-temporal analysis
- ✓ **Connectivity analysis framework**

Benthic habitat characterization

Applications:

- identification of “aggregation areas”
- conservation prioritization
- ecoregional planning
- MPA design



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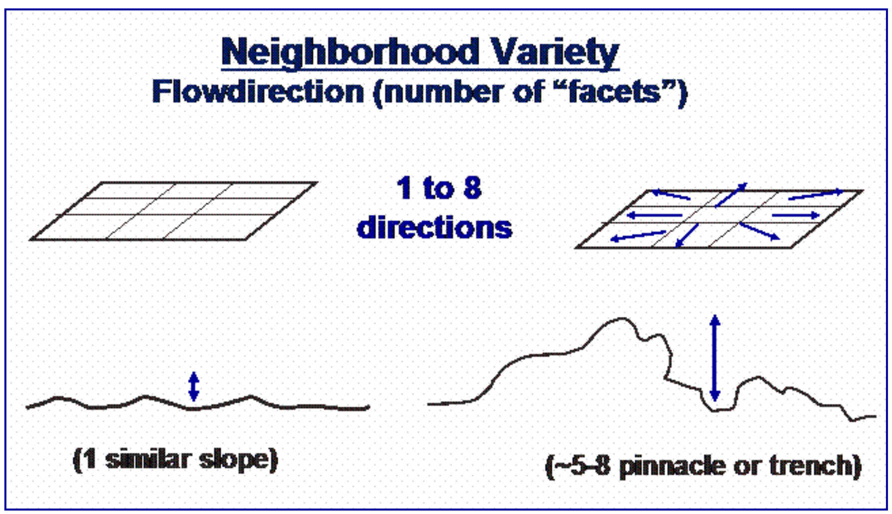
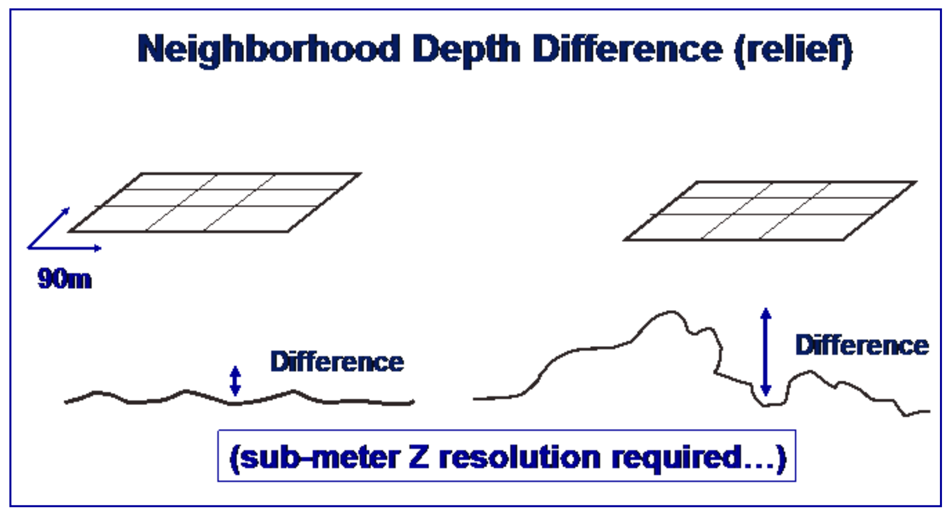
The Nature Conservancy®
Marine Initiative

The Marine Ecoregional Planning Process
deriving marine ecological units:

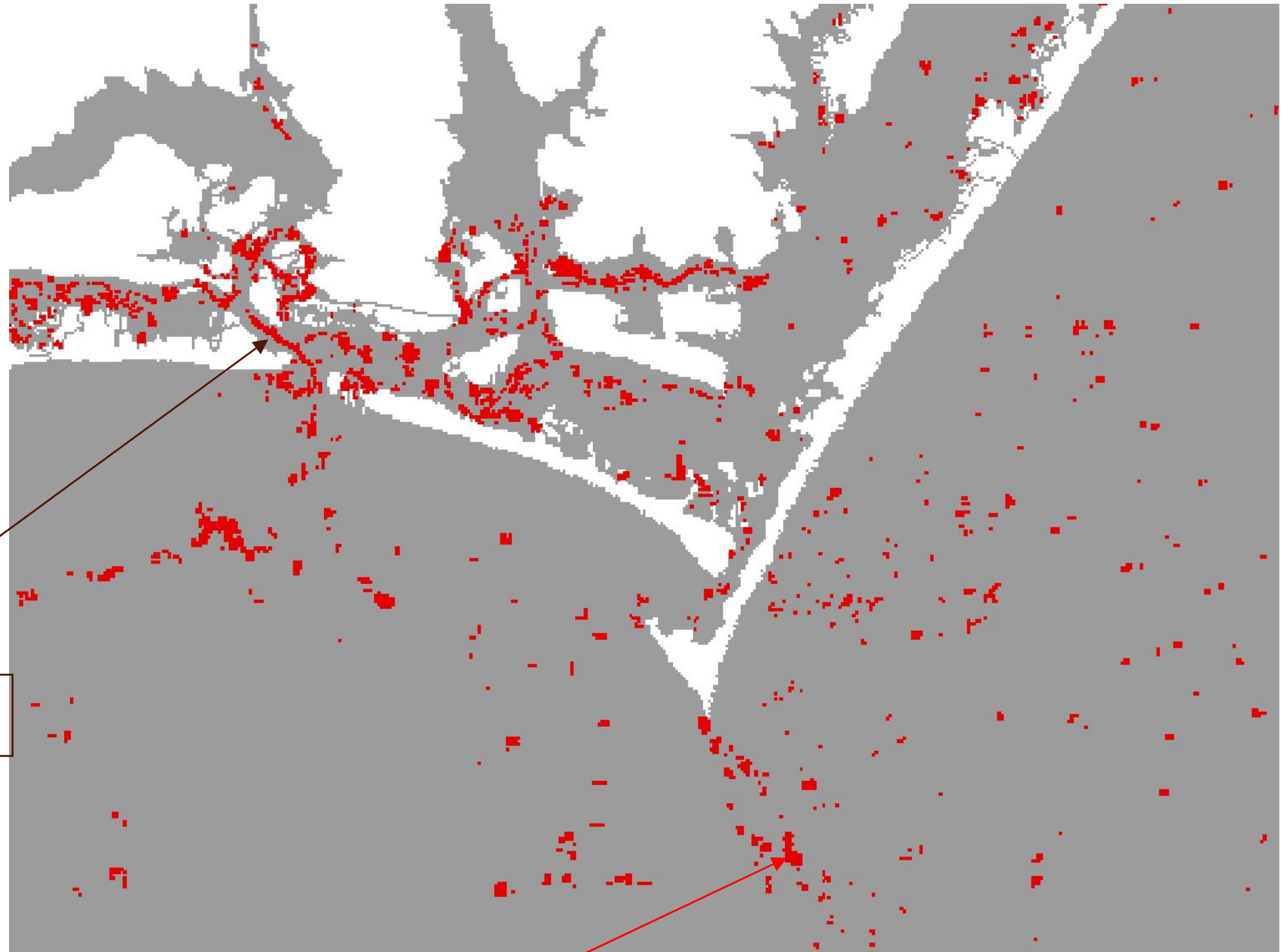
3 depth classes
8 bottom complexity / rugosity types
3 relief classes (flat, low, high)





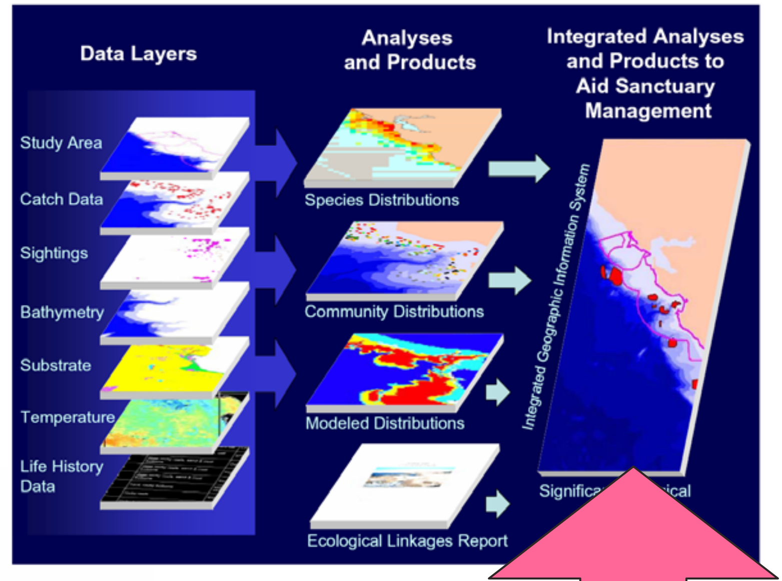
The Marine Ecoregional Planning Process

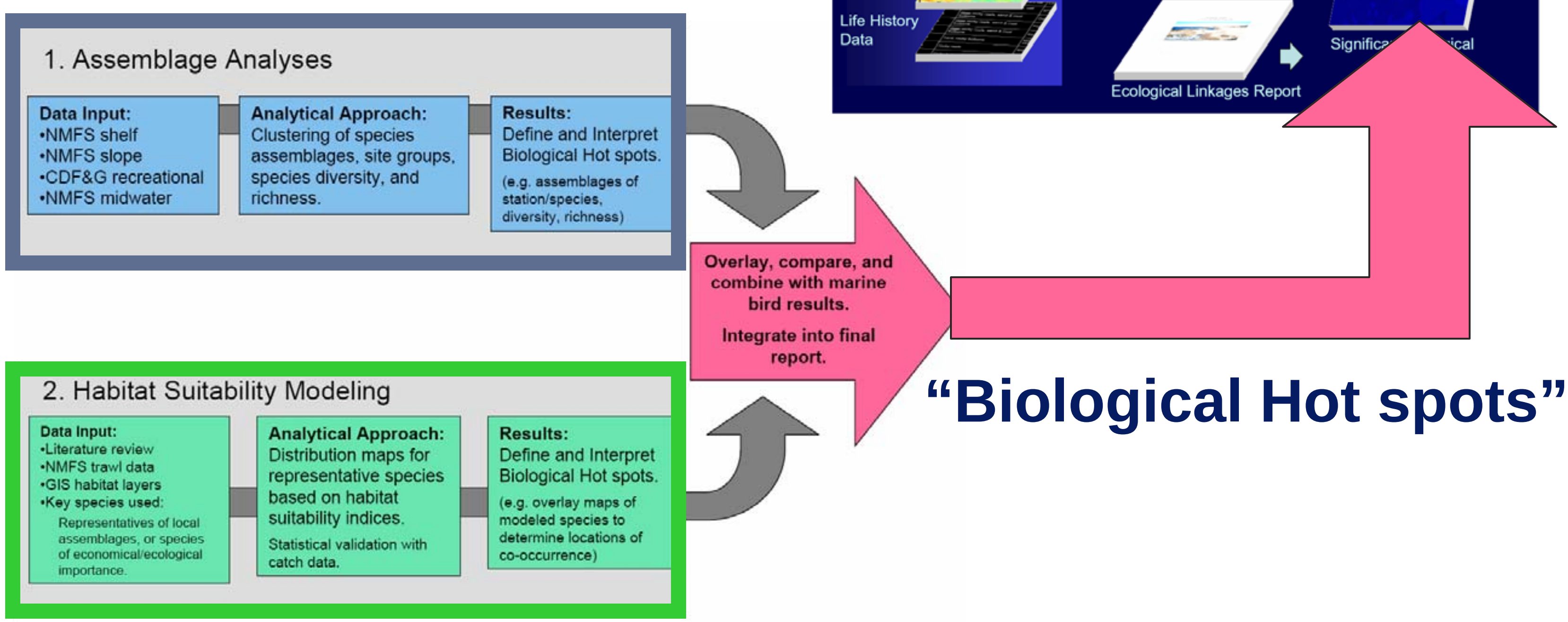
Bottom Complexity (threshold)



dredged channel

potential “natural” benthic complexity





Citation:

NOAA National Centers for Coastal Ocean Science (NCCOS) 2003. A Biogeographic Assessment off North/Central California: To Support the Joint Management Plan Review for Cordell Bank, Gulf of the Farallones, and Monterey Bay National Marine Sanctuaries: Phase I - Marine Fishes, Birds and Mammals. Prepared by NCCOS's Biogeography Team in cooperation with the National Marine Sanctuary Program. Silver Spring, MD 145 pp.

Science needs

Benthic habitat characterization needs…

"Hot spot" analysis is not going to be enough…

Needs:

more objective, spatial & temporal definitions of…

- ✓ **ecosystem processes**
- ✓ **ecosystem functions**
- ✓ **ecosystem dynamics**
- ✓ **ecosystem services**

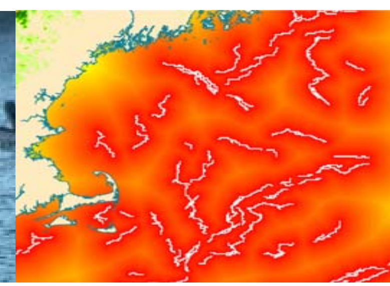
Science needs

- ✓ **Background**
- ✓ **Habitat characterization**
  - ✓ Benthic "habitat"
  - ✓ Pelagic "habitat"
- ✓ **Spatio-temporal modeling**
  - ✓ Habitat modeling
  - ✓ Model evaluation
  - ✓ Spatio-temporal analysis
- ✓ **Connectivity analysis framework**

Pelagic habitat analysis

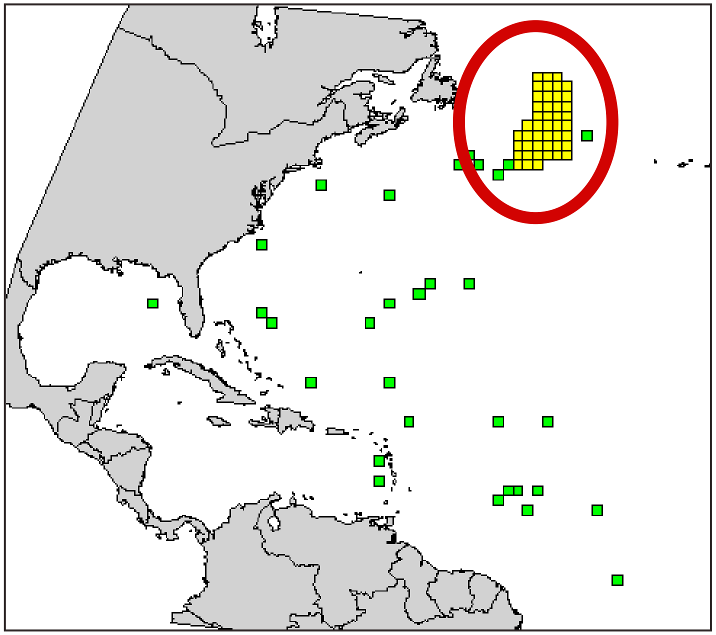
In order to predict the dynamics of marine animal populations and fisheries interactions we need to directly analyze ***animal interactions with oceanographic processes***…




Marine Management Application

Optimizing fisheries closures in space and time.



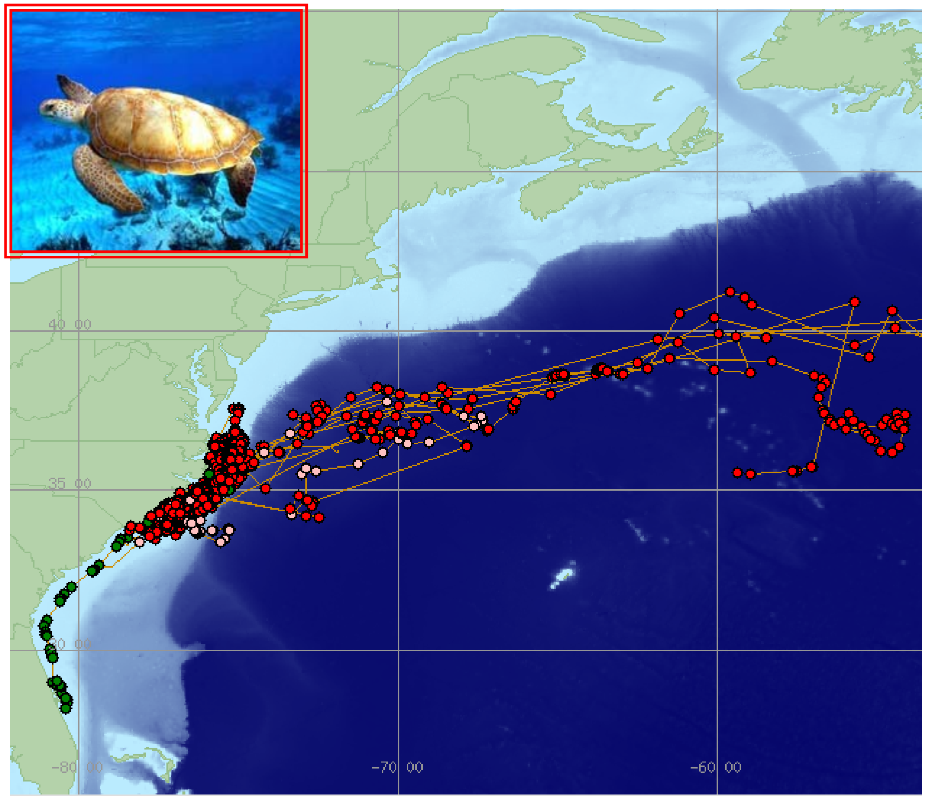
Spatial optimization algorithms used to select potential locations to reduce sea turtle bycatch in the Atlantic swordfish fishery.

***D'Agrosa**, C., A.J. Read, P. N. Halpin, M.A. Hall. (2004 - in prep.) Reducing the ecological cost of the US Atlantic swordfish longline fleet: Tools for incorporating spatial distribution into time-area closure design.*

Pelagic Habitat Characterization

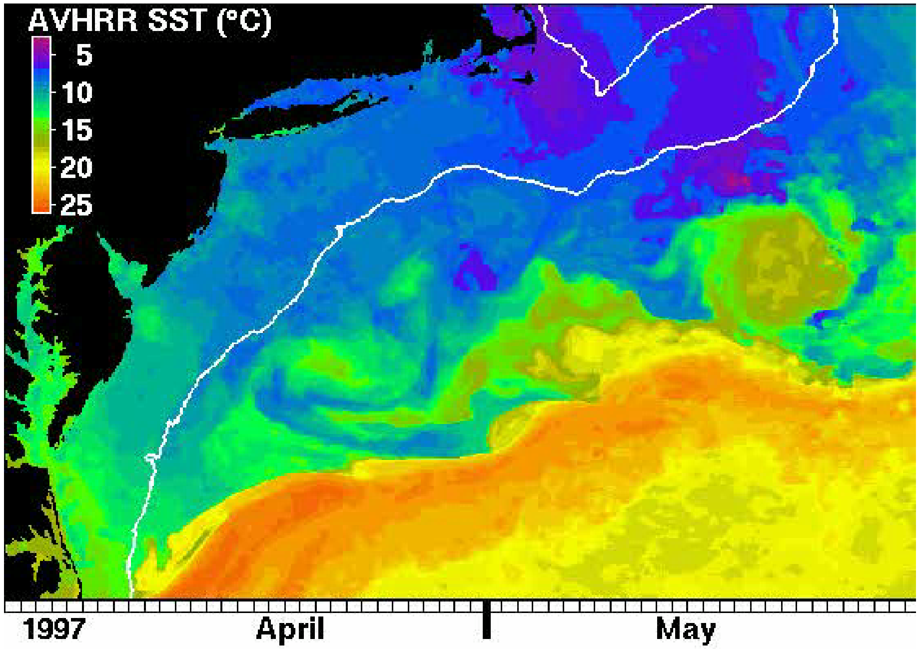
Animal Tracking (telemetry location series)

Sea Turtle Tracks *(Caretta caretta)*



Source: http://obis.env.duke.edu/datasets/
(Read & McClellan2004)

Sea Surface Temperature (WCR)

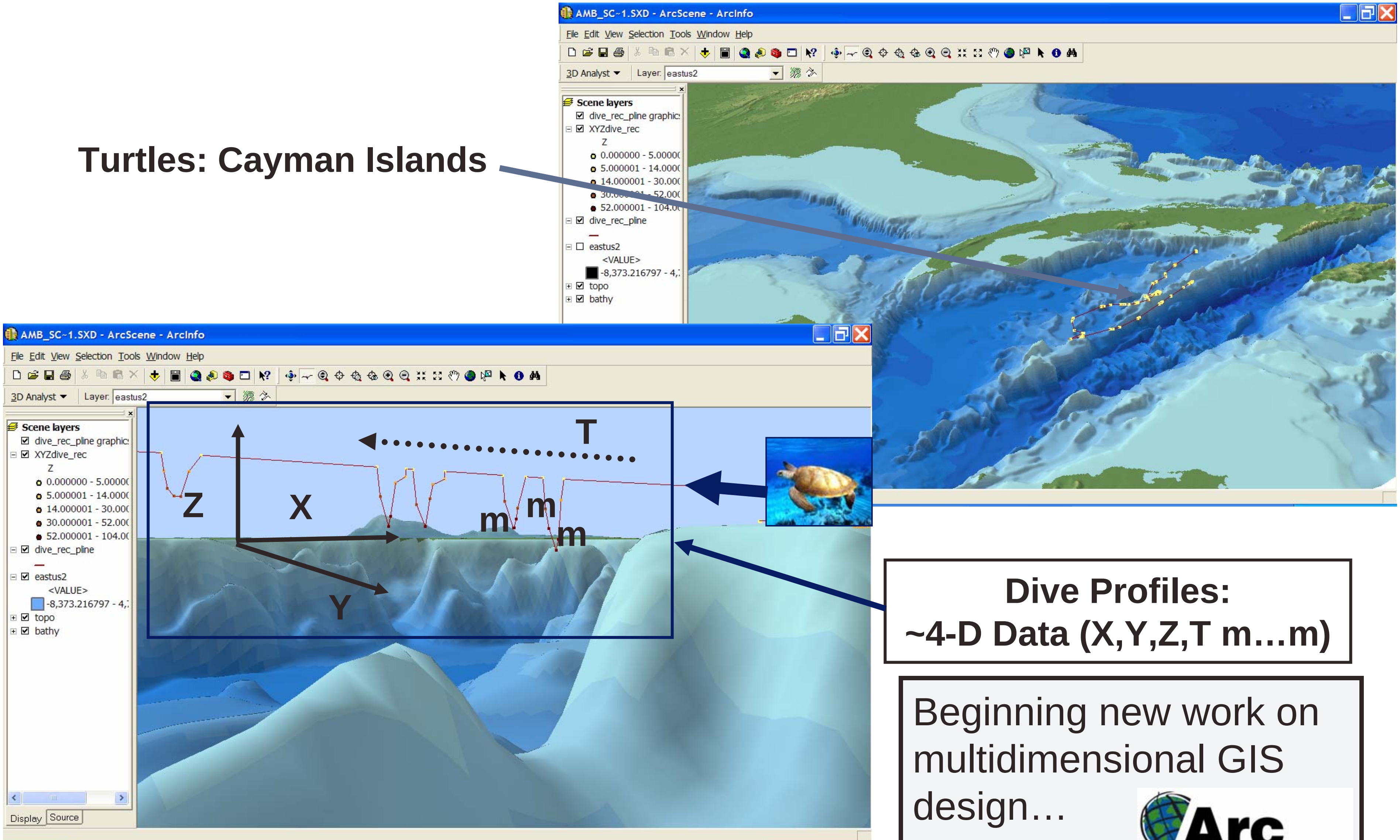


Source: http://www.po.gso.uri.edu/SST/

…are animals tracking prey along oceanographic features?
(e.g. outer edge of a warm-core ring…)

Animal Tracking (telemetry location series)

Turtles: Cayman Islands



Dive Profiles:
~4-D Data (X,Y,Z,T m…m)

Beginning new work on multidimensional GIS design…

Science needs

Pelagic habitat characterization needs…

"Mapping spatial pattern is not going to be enough…

Needs:

- **more objective, spatial definitions of…**
  - ✓ **animal behavior / responses**
  - ✓ **spatio-temporal modeling**
  - ✓ **spatio-temporal management**

Science needs

- ✓ **Background**
- ✓ **Habitat characterization**
  - ✓ Benthic “habitat”
  - ✓ Pelagic “habitat”
- ✓ **Spatio-temporal modeling**
  - ✓ Habitat modeling
  - ✓ Model evaluation
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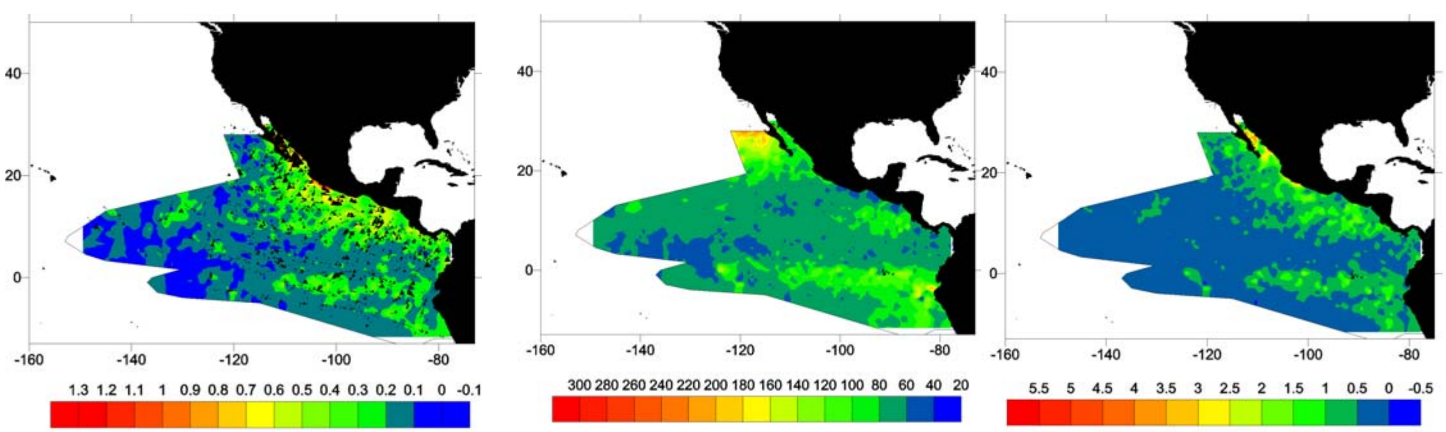
- ✓ **Connectivity analysis framework**

Types of models – Types of questions

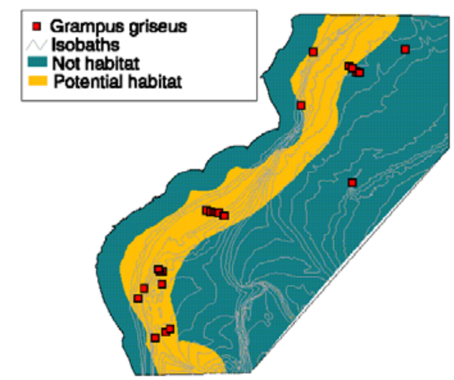
- ✓ Habitat preference / environmental affinity
- ✓ Behavior / response
- ✓ Density / abundance
- ✓ Forecasting / probabilistic encounter
- ✓ Management / optimization

Encounter Rate Model (n/L) | **Group Size Model (s)** | **Density Model (D)**



From: J. Barlow, et. al 2003. SERDP program presentation

Habitat Model



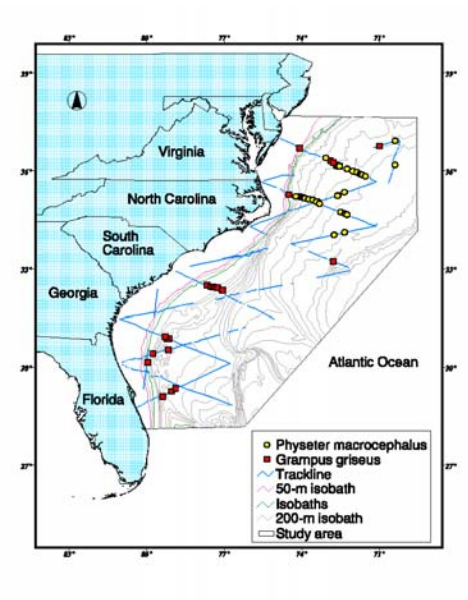
D'Agrosa & Halpin 2000

DoD EPA DOE SERDP Strategic Environmental Research and Development Program

2 modeling projects: SWFSC & Duke University

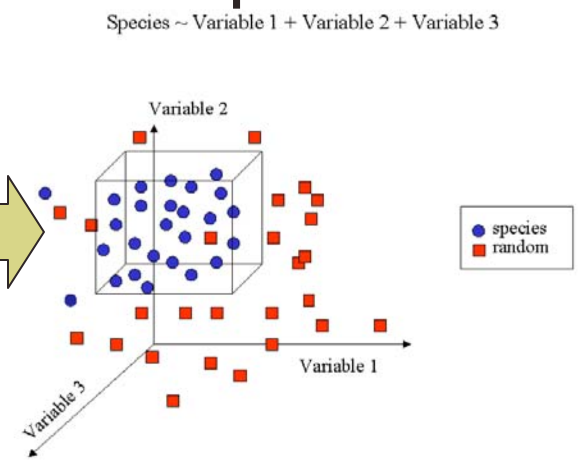
Typical marine animal habitat modeling approach

Geographic Space



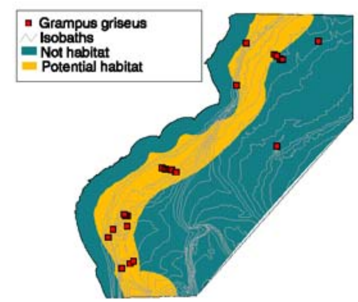
Sample Data

Statistical Applications
Data Space



Redefine Model

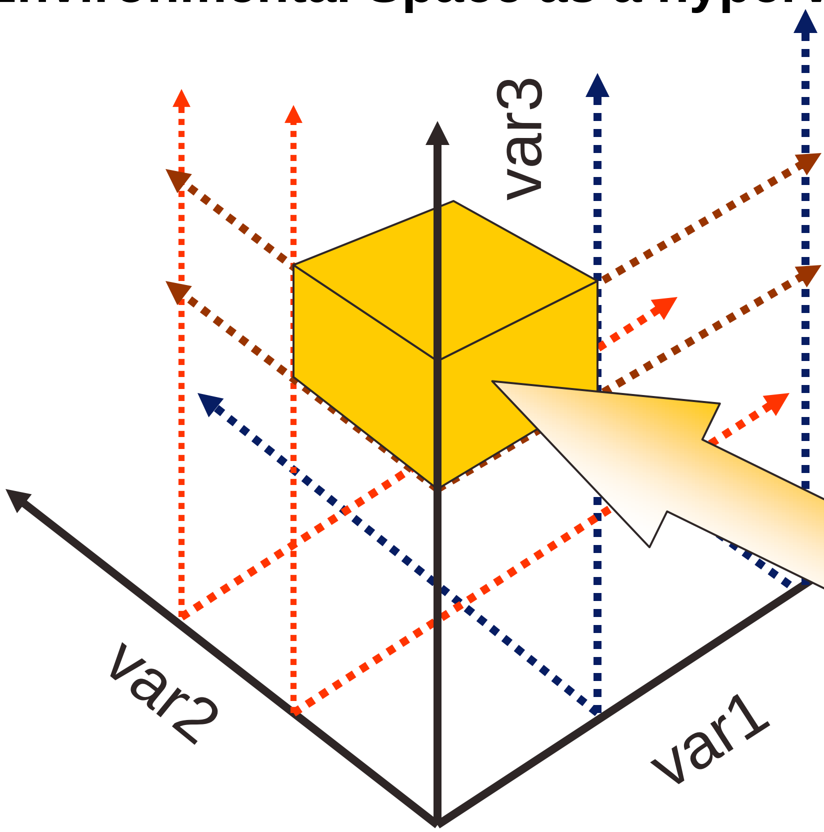
Geographic Space

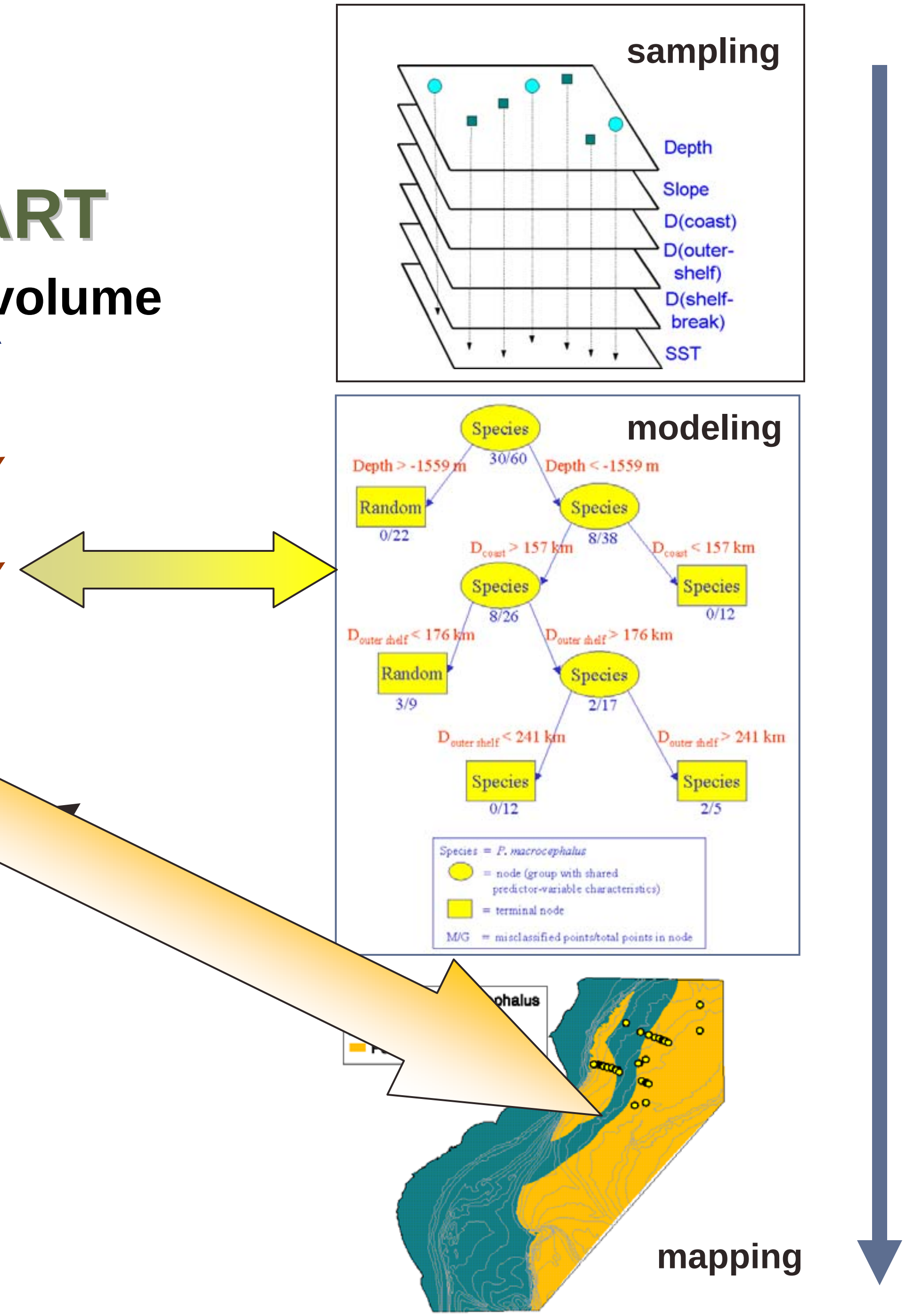


Model Habitat

Classification: CART

Environmental Space as a hypervolume





Depth
Sea Surface Temp
Distance from shelf break

Modeling example:

Sperm Whale: Physeter macrocephalus

Two NEFSC Data sets

NEFSC 98 1

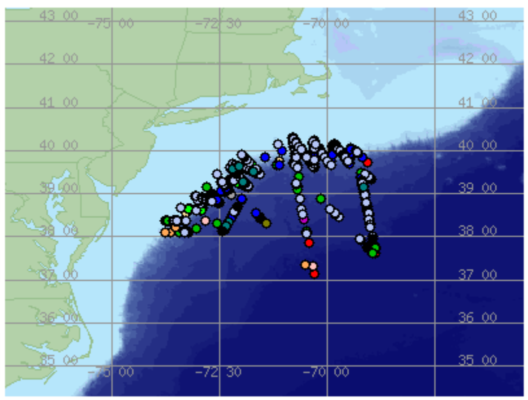
ID	60
# of Records	505
Date, Begin	1998-Jul-8
Date, End	1998-Aug-3
Latitude, Min	37.14
Latitude, Max	40.30
Longitude, Min	-73.77
Longitude, Max	-68.88

View Species Recorded

View Metadata

Download Data

Download Shapefile



larger image
interactive map

Citation

Palka, Debi. 1998. Northeast Fisheries Science Center 1998 Survey 1.

Sponsor: NOAA Northeast Fisheries Science Center (NEFSC)

NEFSC 98 2

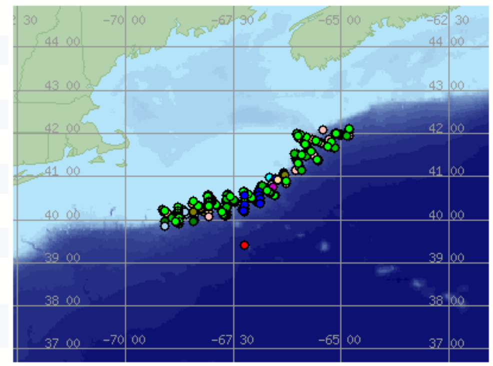
ID	62
# of Records	315
Date, Begin	1998-Aug-9
Date, End	1998-Aug-31
Latitude, Min	39.40
Latitude, Max	42.10
Longitude, Min	-69.13
Longitude, Max	-64.80

View Species Recorded

View Metadata

Download Data

Download Shapefile



larger image
interactive map

Citation

Palka, Debi. 1998. Northeast Fisheries Science Center 1998 Survey 2.

Sponsor: NOAA Northeast Fisheries Science Center (NEFSC)

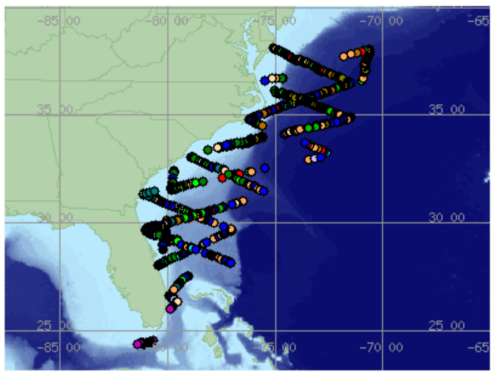
Modeling example:
Sperm Whale: Physeter macrocephalus

Two SEFSC Data sets

SEFSC Atlantic surveys, 1998 (3)

ID	1
# of Records	1073
Date, Begin	1998-Jul-9
Date, End	1998-Aug-20
Latitude, Min	24.37
Latitude, Max	38.14
Longitude, Min	-81.40
Longitude, Max	-70.61

View Species Recorded
View Metadata
Download Data
Download Shapefile



larger image
interactive map

Citation

Roden, C. 1998. Summer Atlantic Ocean Marine Mammal Survey. Southeast Fisheries Science Center, NOAA.

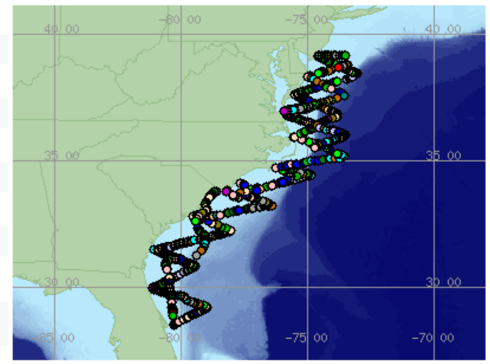
Sources: Cruise Results; Summer Atlantic Ocean Marine Mammal Survey; NOAA Ship Relentless Cruise RS 98-01 (3).

Sponsor: NOAA Southeast Fisheries Science Center (SEFSC)

SEFSC Atlantic surveys, 1999 (236)

ID	5
# of Records	1247
Date, Begin	1999-Aug-9
Date, End	1999-Sep-25
Latitude, Min	28.52
Latitude, Max	39.16
Longitude, Min	-81.14
Longitude, Max	-73.05

View Species Recorded
View Metadata
Download Data
Download Shapefile



larger image
interactive map

Citation

Roden, C. 1999. Summer Atlantic Ocean Marine Mammal Survey. Southeast Fisheries Science Center, NOAA.

Sources: Cruise Results; Summer Atlantic Ocean Marine Mammal Survey; NOAA Ship Oregon II Cruise OT 99-05 (236)

Sponsor: NOAA Southeast Fisheries Science Center (SEFSC)

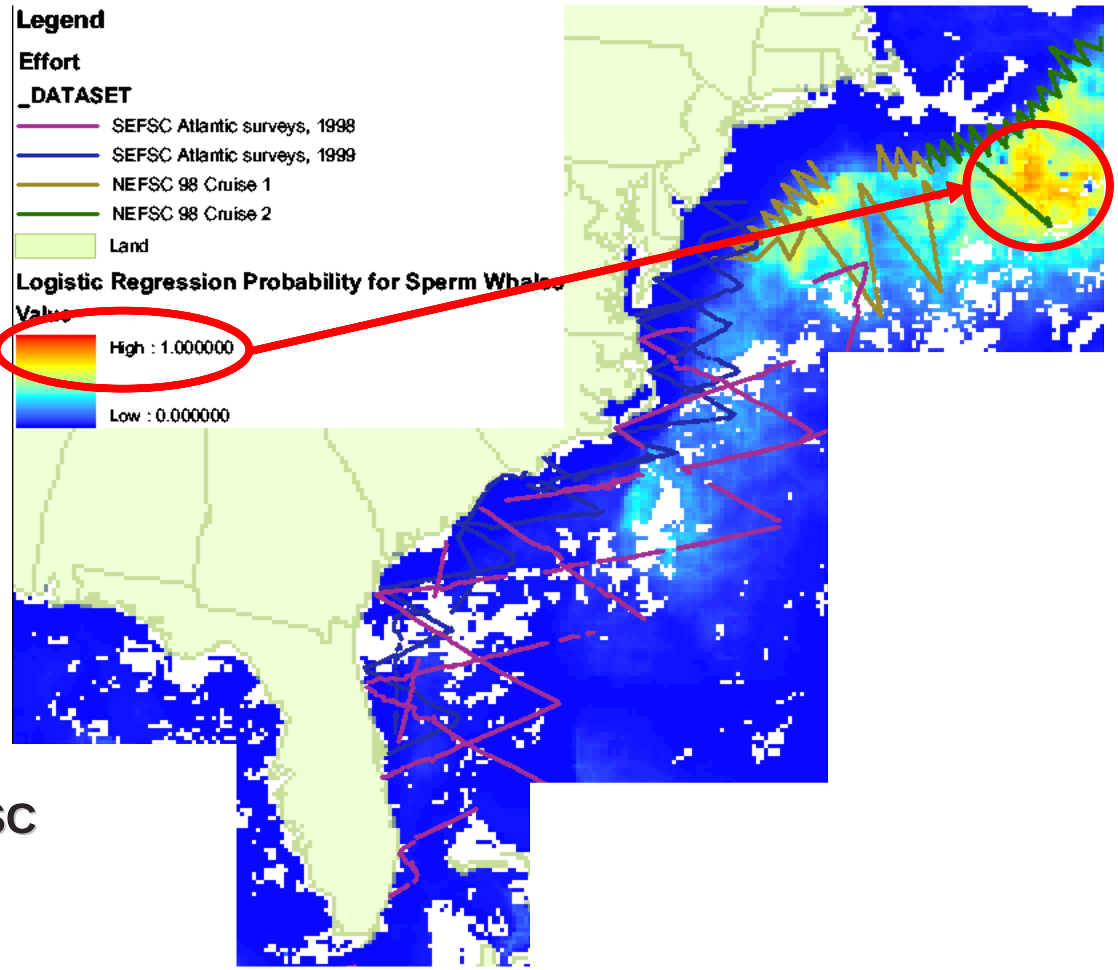
Modeling example:
Sperm Whale: Physeter macrocephalus

Physeter macrocephalus

0 - 100% probability range
No threshold set for habitat
***.vs* non-habitat**

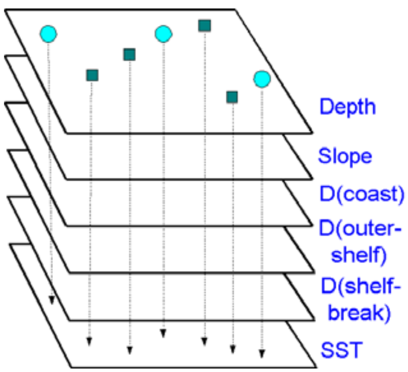
Model output calculated for: oceanographic conditions, August 5-12 1998

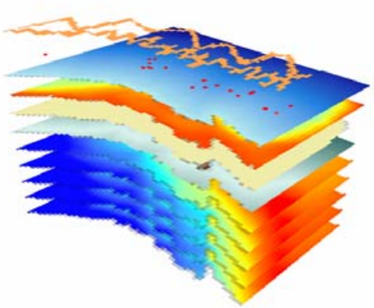
Data Sources: NEFSC & SEFSC

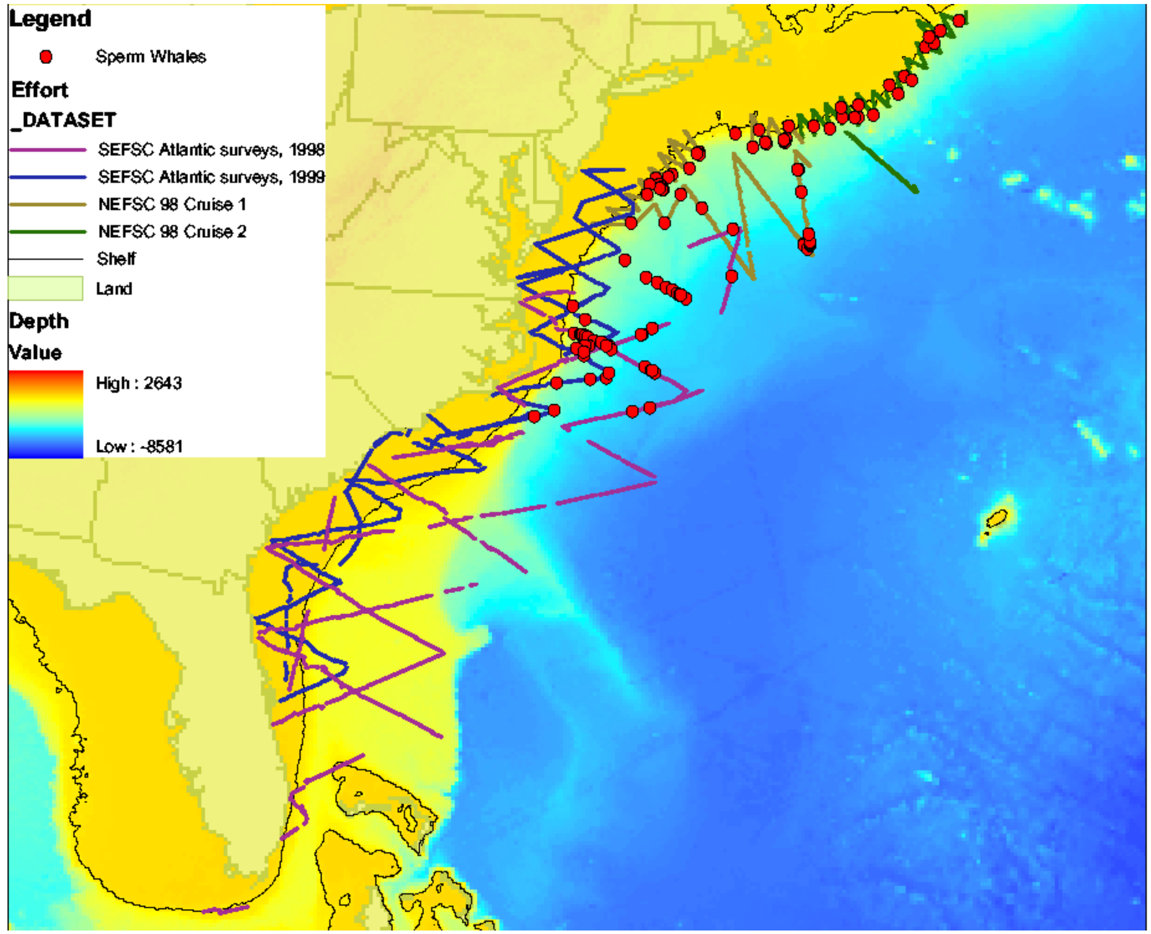


Modeling example:
Sperm Whale: Physeter macrocephalus

Sample points
vs. random points



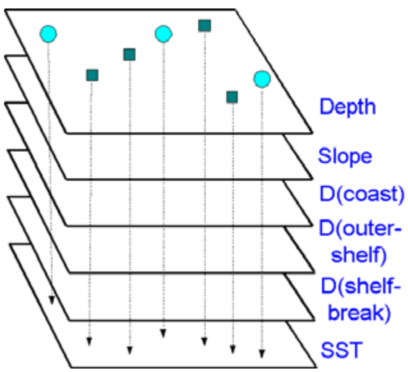


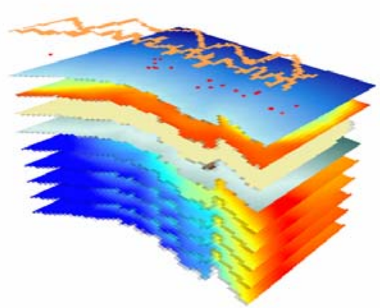


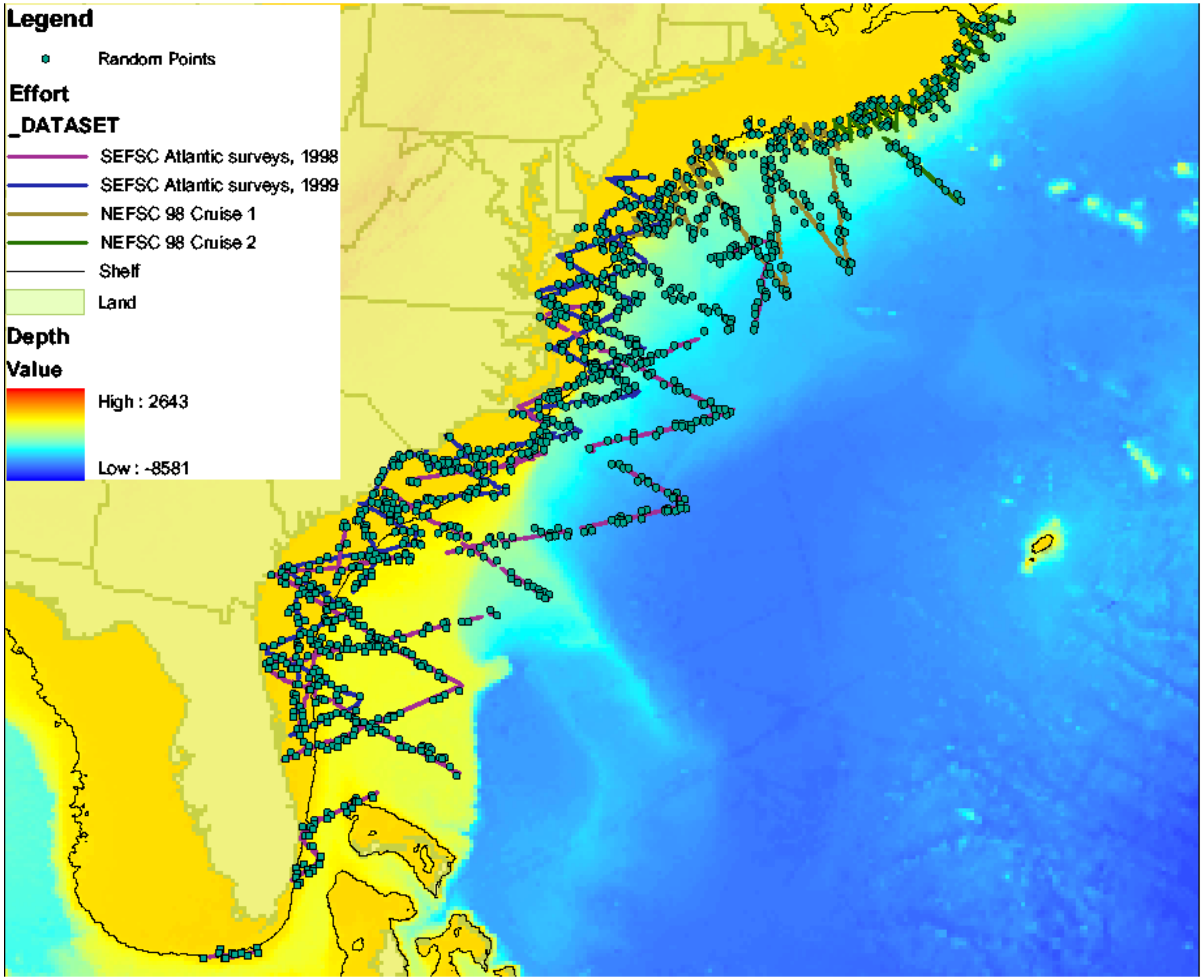
Data Sources: NEFSC & SEFSC

Modeling example:
Sperm Whale: Physeter macrocephalus

Sample points
vs. **random** points





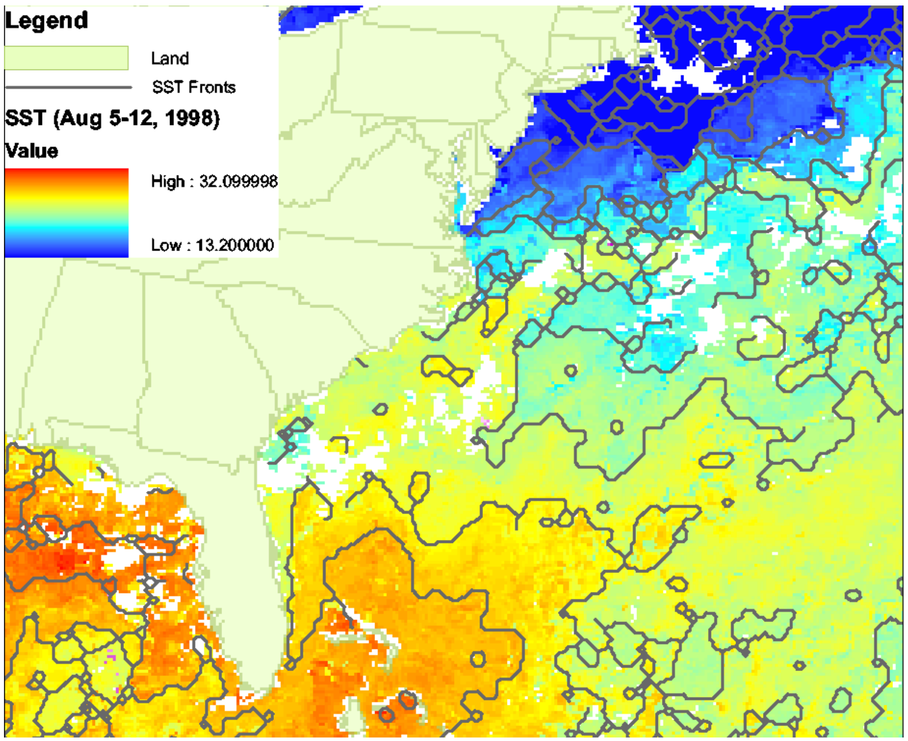


Data Sources: NEFSC & SEFSC

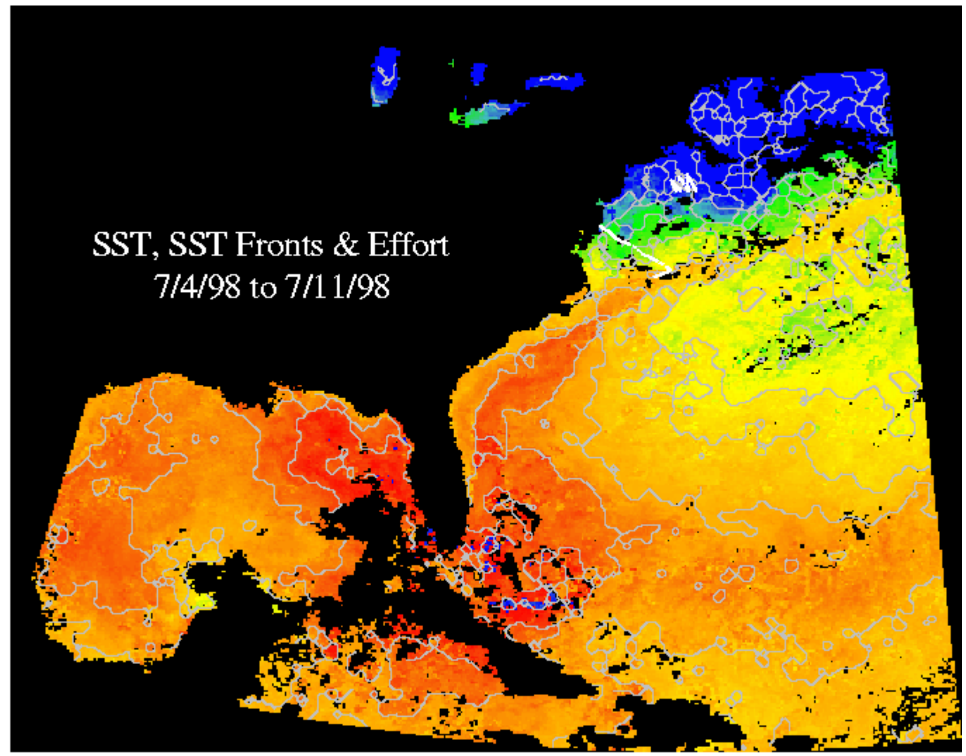
Modeling example:

Sperm Whale: Physeter macrocephalus

Relating spatio-temporal environment



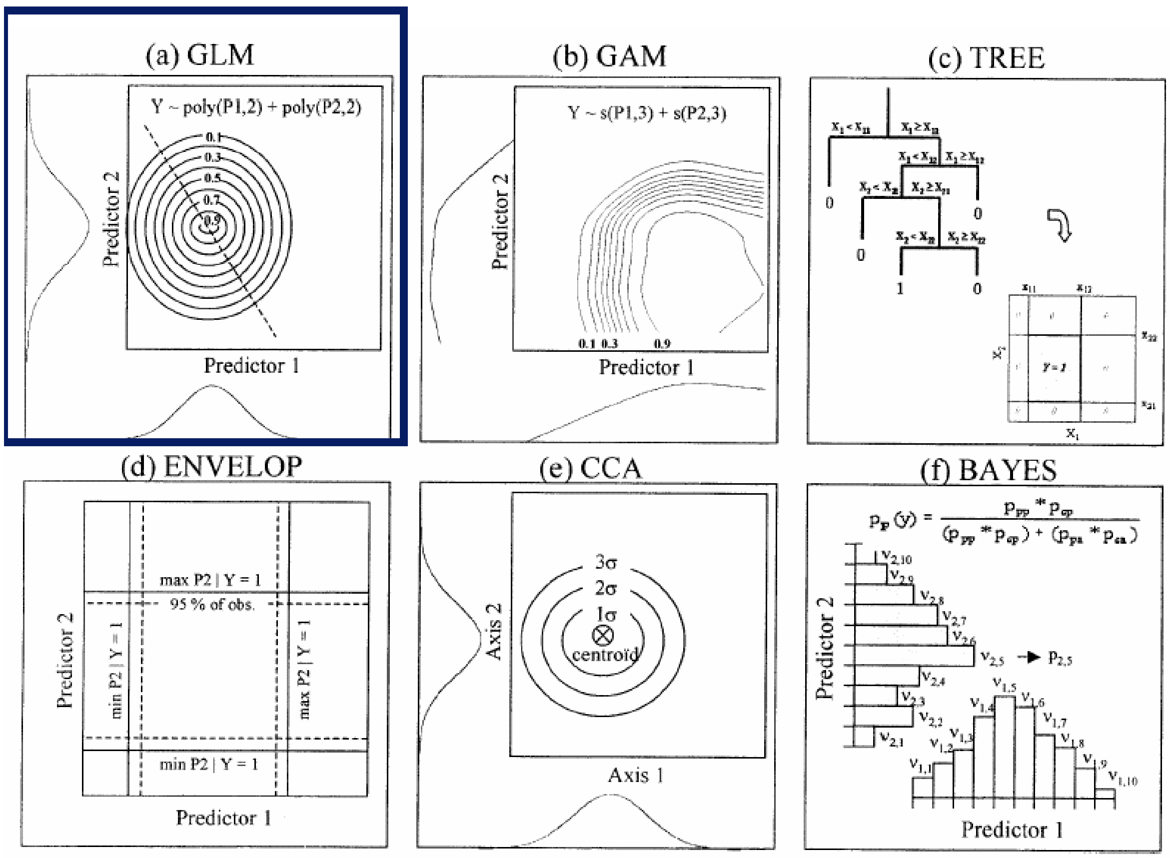
Distance from front



Temporal series of sampling effort & environment

Types of models

Different Statistical Approaches to Ecological Habitat Modeling



Source: Guisan & Zimmermann, 2000.

Logistic Regression

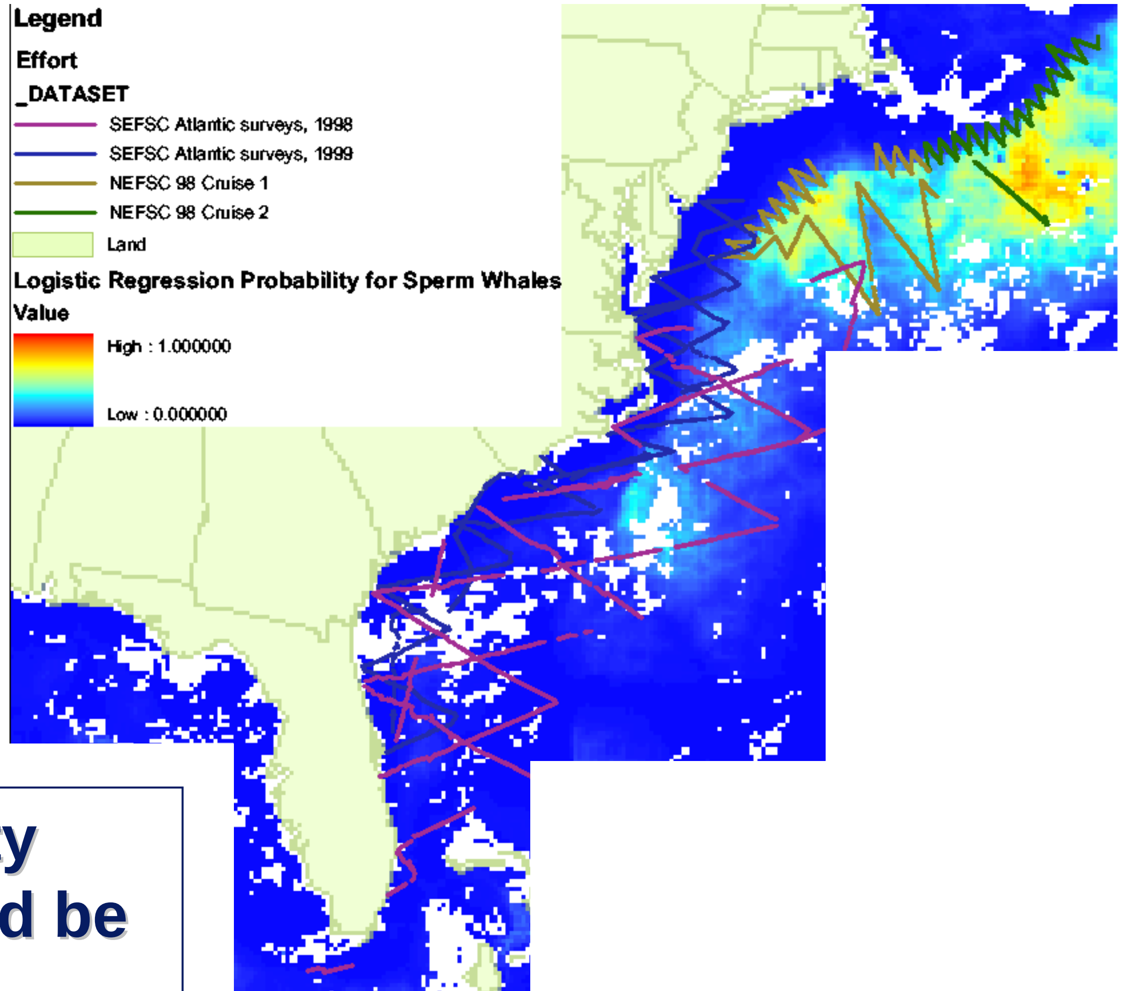
- (a) **Generalized Linear Model** with second order polynomial terms;
- (b) **Generalized Additive Model** with smoothed spline functions;
- (c) **Classification Tree (CART)**;
- (d) **Environmental Envelope** models
- (e) **Canonical Correspondence Analysis**;
- (f) **Bayesian models** according to Aspinall (1992);

*p*p posterior probability of presence of the modeled species, *p*pp a priori probability of presence, *p*pa a priori probability of absence, *p*cp product of *conditional* probability of presence of the various predictor classes, *p*ca product of *conditional* probability of absence of the various predictor classes.

Sperm Whale: Physeter macrocephalus (P. catadon)

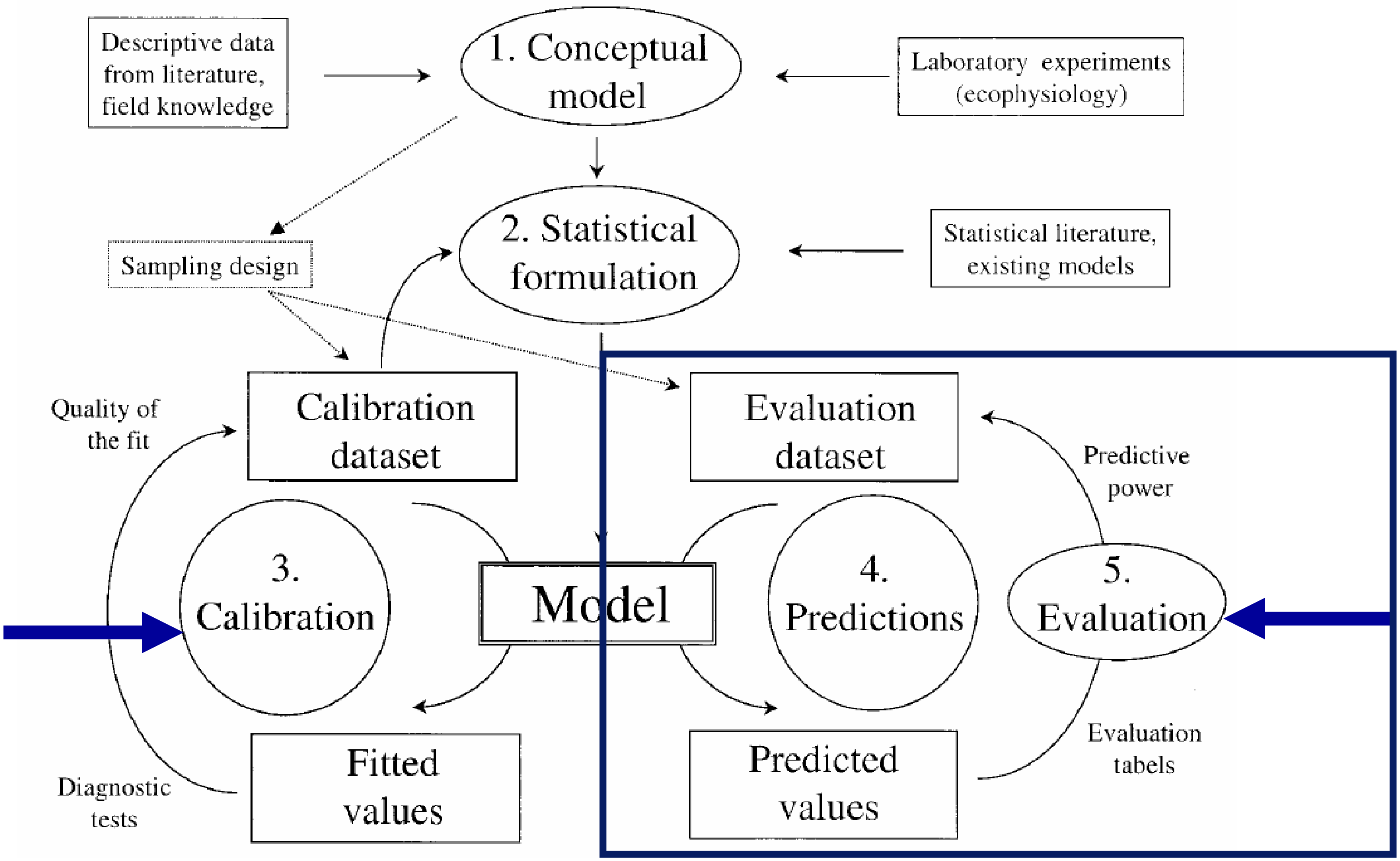
0 - 100% probability range
No threshold set for habitat
***.vs* non-habitat**

Model output calculated for: oceanographic conditions, August 5-12 1998



What probability threshold should be used?

Potential Habitat Model: Process



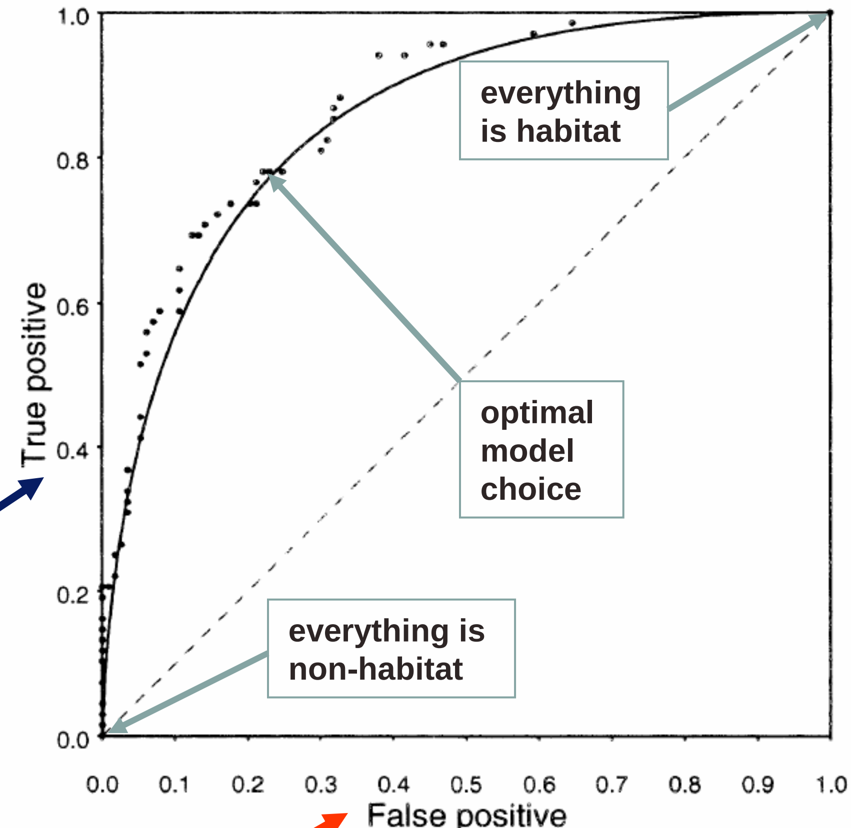
From: Guisan and Zimmermann 2000

ROC: Receiver Operator Curves

- Select the optimal threshold (***not just guess at >0.5 probability***)
- Maximum sensitivity and specificity

Sensitivity = a/a+b (true positive)
Specificity = d/b+d (true negative)

The 45° line represents the sensitivity and false positive values expected to be achieved by chance alone for each decision threshold.



True Positive Fraction

	Recorded present	Recorded absent	
Predicted present	A	B	$A + B$
Predicted absent	C	D	$C + D$
	$A + C$	$B + D$	$A + B + C + D$

False Positive Fraction

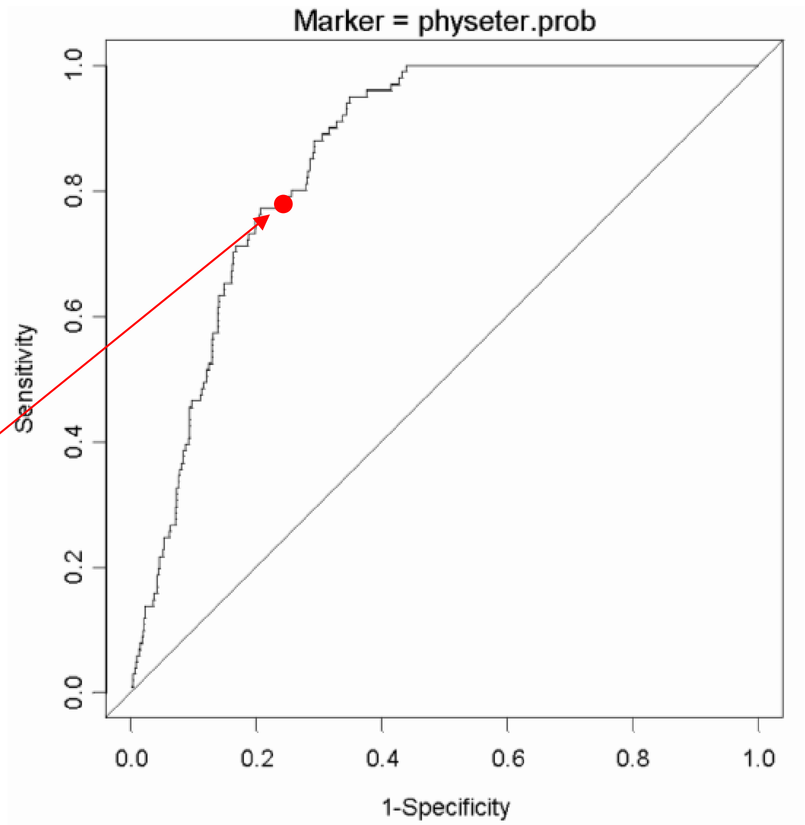
ROC: Receiver Operator Curves

Evaluating the model with ROC

The 'best' cutoffs maximizing sensitivity and specificity:

When minimizing sqrt((1-sensitivity)^2 + (1-specificity)^2)

	Marker value	Sensitivity	Specificity
physeter.prob	**0.1153072**	0.7722772	0.7934694



Evaluating the Area Under the Curve (AUC)

Markers:

ROC	AUC	Cont(0): n	mean	std.dev	cv	Case(1): n	mean	std.dev	cv
physeter.prob	**0.86**	1225	0.0661	0.0938	1.4	101	0.198	0.117	0.59

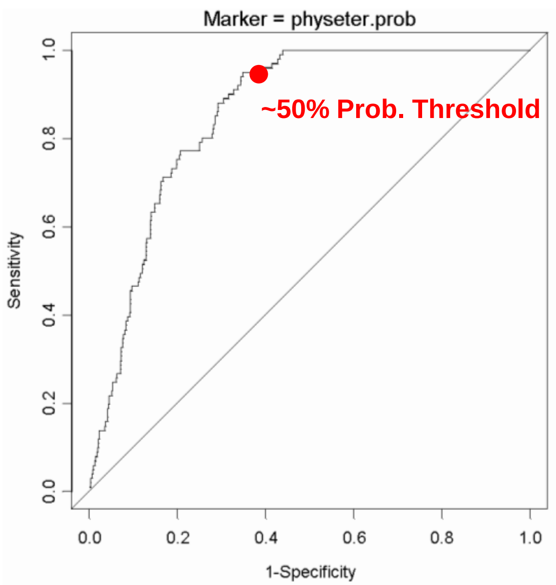
An Area Under the Curve (AUC) >0.9 is excellent, so a value of 0.86 is "very good".

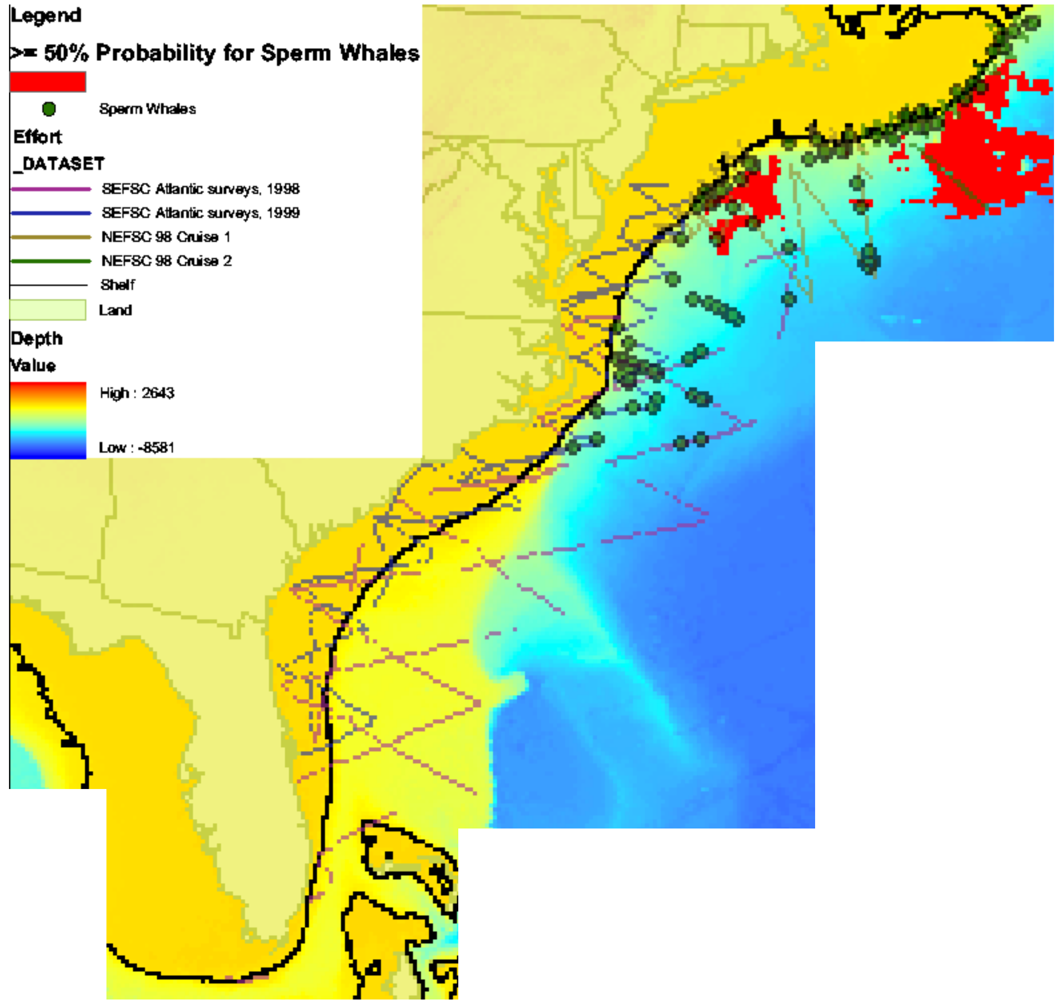
(AUC ranges from 0.5 – 1.0)

Sperm Whale: Physeter macrocephalus (P. catadon)

Using a >50% probability threshold:

Too conservative
many “errors of omission”



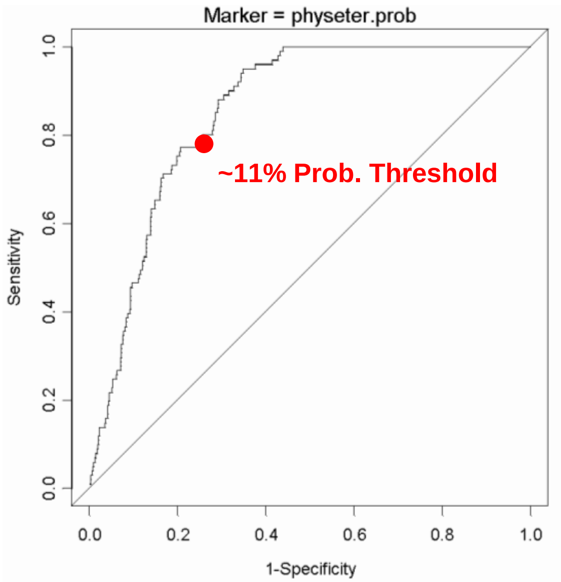


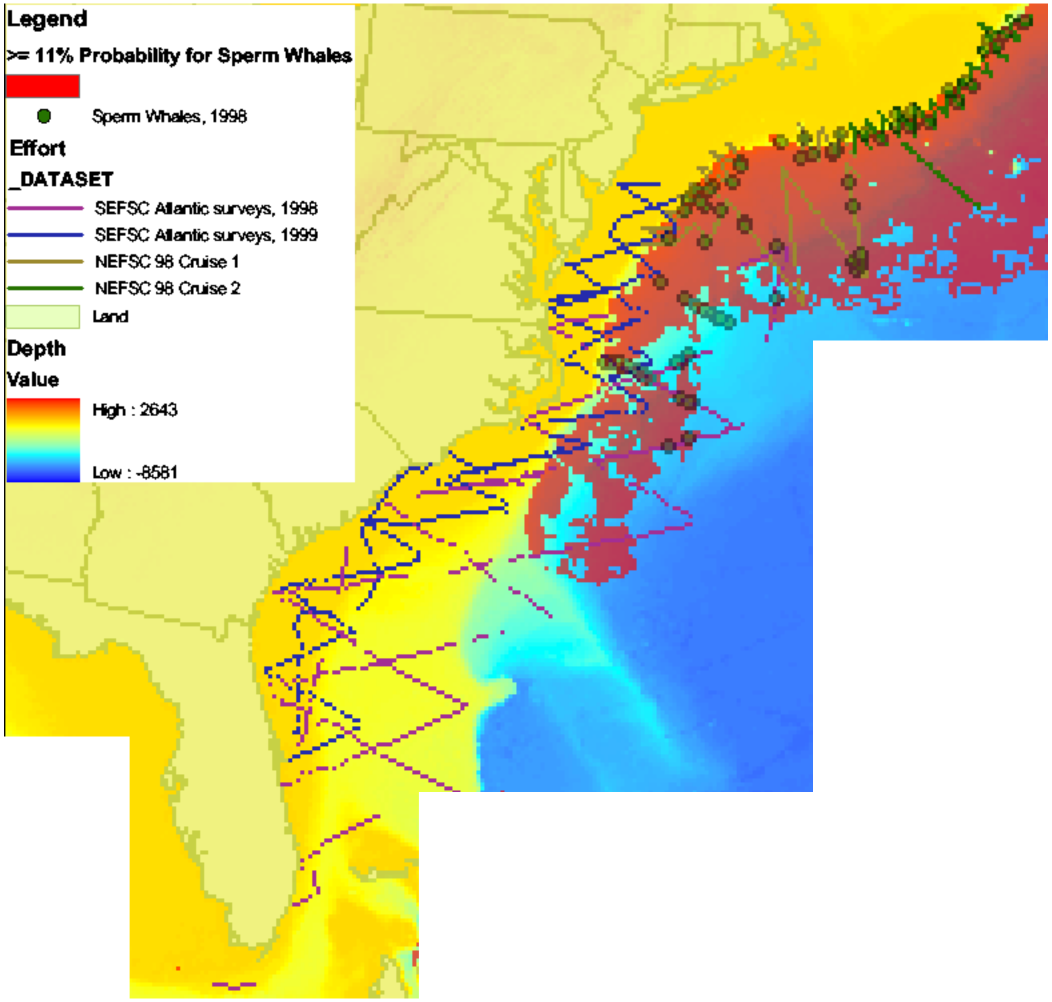
Model output calculated for: oceanographic conditions, August 5-12 1998

Sperm Whale: Physeter macrocephalus (P. catadon)

Using a >11% probability threshold:

Optimizes "errors of omission" vs. "errors of commission"

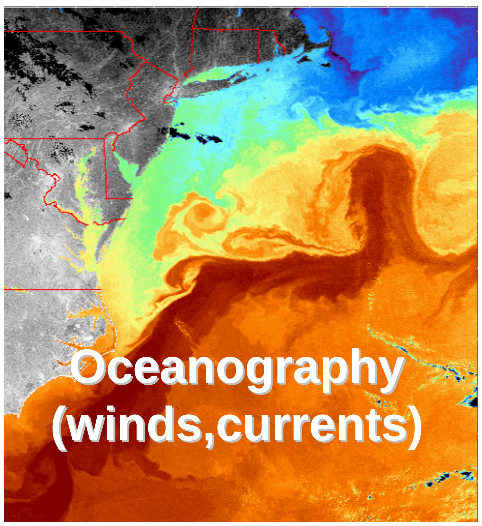




Model output calculated for: oceanographic conditions, August 5-12 1998

Spatio - temporal habitat modeling

At large spatial scales:

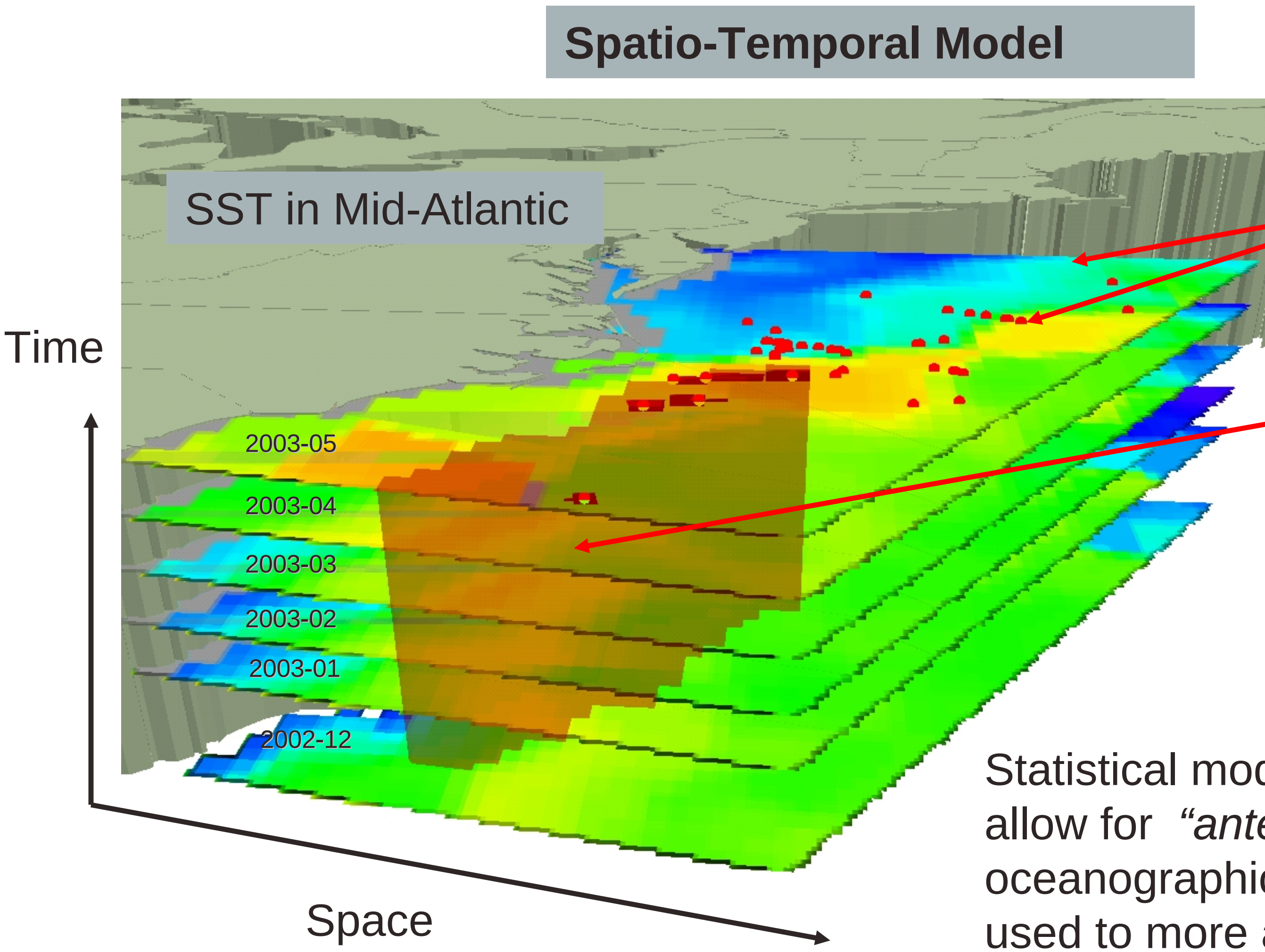


Temporal lags

At finer spatial scales:

Bathymetric and water temperature gradients → Prey availability → Marine mammal distribution

Marine animal habitat modeling

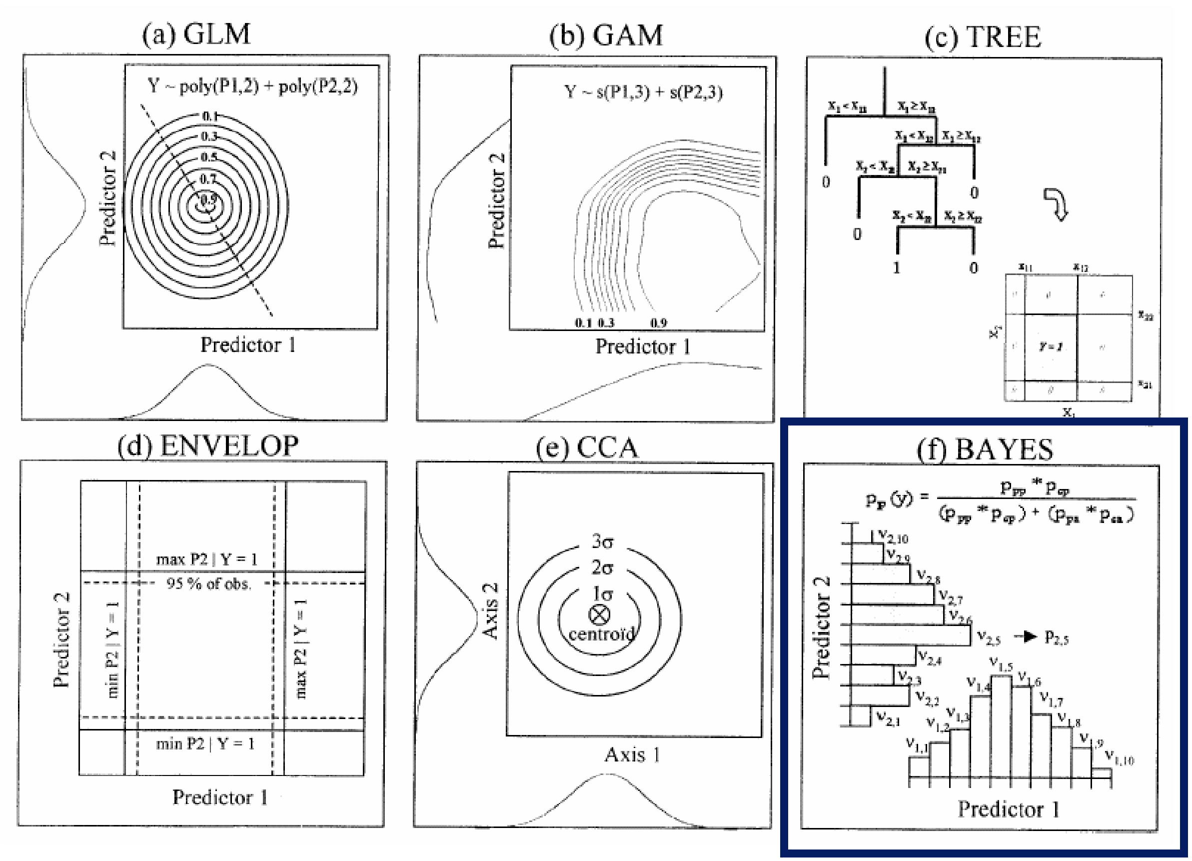


Statistical modeling approach will allow for *"antecedent"* oceanographic conditions to be used to more accurately predict potential habitat.

SERDP
Strategic Environmental Research and Development Program

Types of models

Different Statistical Approaches to Ecological Habitat Modeling



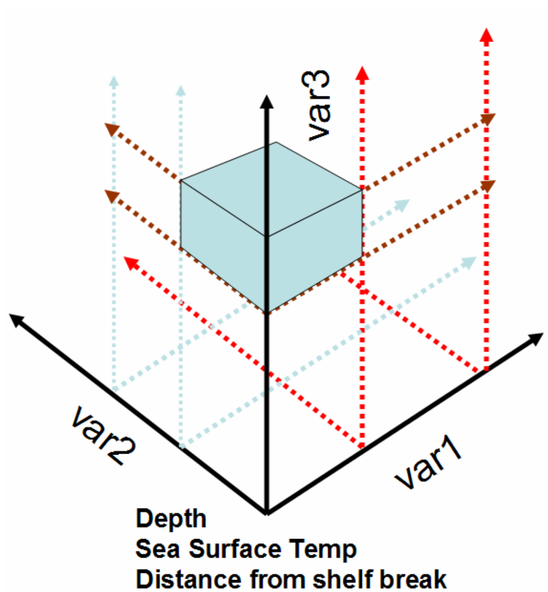
Source: Guisan & Zimmermann, 2000.

- (a) **Generalized Linear Model** with second order polynomial terms;
- (b) **Generalized Additive Model** with smoothed spline functions;
- (c) **Classification Tree (CART)**;
- (d) **Environmental Envelope** models
- (e) **Canonical Correspondence Analysis**;
- (f) **Bayesian models** according to Aspinall (1992);

pp posterior probability of presence of the modeled species, *ppp* a priori probability of presence, *ppa* a priori probability of absence, *pcp* product of *conditional* probability of presence of the various predictor classes, *pca* product of *conditional* probability of absence of the various predictor classes.

Marine animal habitat modeling

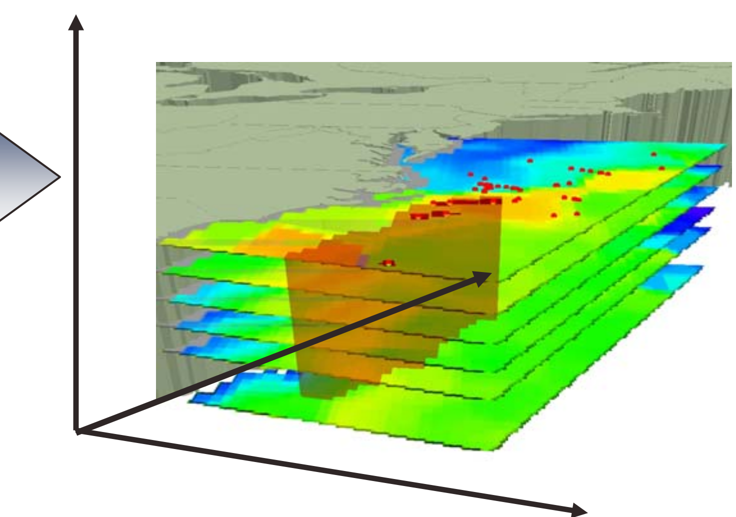
habitat models



Environmental variables associated by space

Example case:
if temperature (x) & productivity (y) & depth (d)
the probability of occurrence ~p

Spatio-temporal habitat models



Environmental variables associated by space & time

Example case:
if temperature (x) & productivity (y)
persist for time limits > (t) and spatial connectivity constraints < (s)
the probability of occurrence ~p

Science needs

Spatio-temporal modeling needs…

"In order to predict dynamic behavior we need to model dynamic behavior…

Needs:

more objective, spatial-temporal models of…

- ✓ animal responses to ocean dynamics
- ✓ time lagged ecosystem processes
- ✓ responses to antecedent conditions
- ✓ better model evaluation / decision support tools

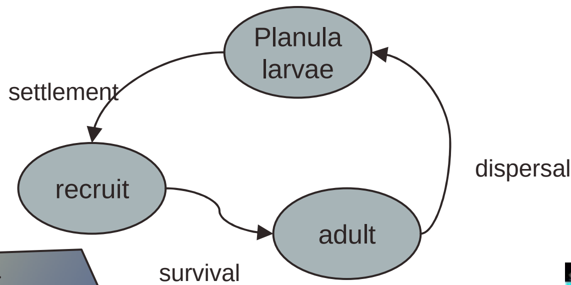
Science needs

- ✓ **Background**
- ✓ **Habitat characterization**
  - ✓ Benthic "habitat"
  - ✓ Pelagic "habitat"
- ✓ **Spatio-temporal modeling**
  - ✓ Habitat modeling
  - ✓ Model evaluation
  - ✓ Spatio-temporal analysis
- ✓ **Connectivity analysis framework**

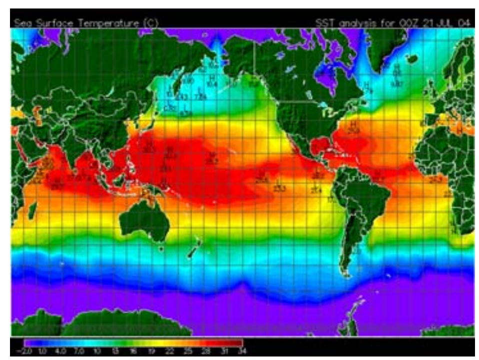
MPA network design analysis

coral ecology

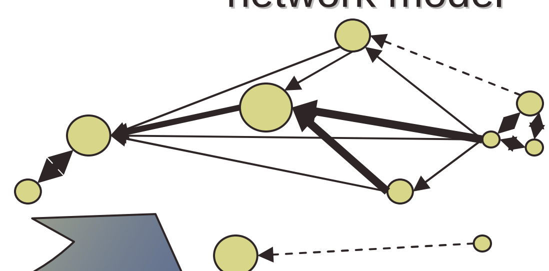
conceptual model



hydrodynamic model



network model



$$\frac{\partial L}{\partial t} = K\left[\frac{\partial^2 L}{\partial^2 x^2} + \frac{\partial^2 L}{\partial^2 y^2}\right] - u\frac{\partial L}{\partial x} - v\frac{\partial L}{\partial y} - \lambda L$$

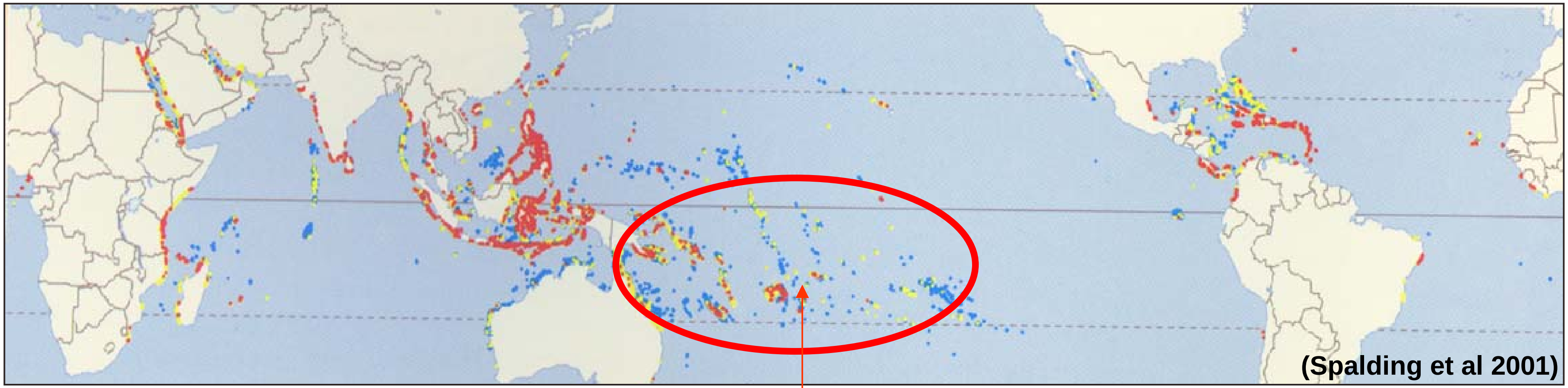
$$\frac{\partial B_{xy}}{\partial t} = c_t F L_{shore} - \mu B$$

$$K\left(\frac{\partial L}{\partial x}\right)_{shore} = mB - c_t F L_{shore}$$

Running “particle tracking” in commercial GIS systems is generally not feasible…

Combining Hydrodynamic & Network models

This project required significant development outside of the GIS



Centered on American Samoa

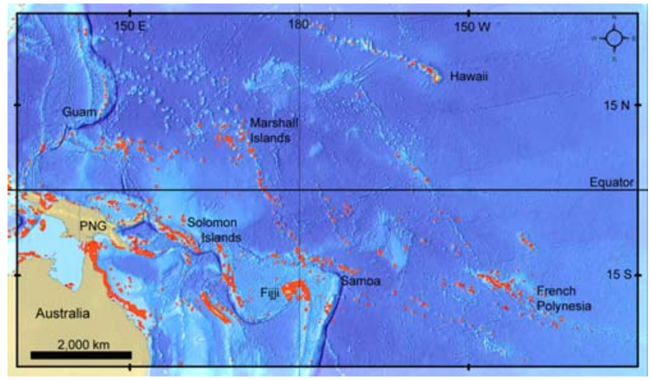
Eric Treml Ph.D. Candidate

former NOAA Coastal Services Center GIS Analyst…

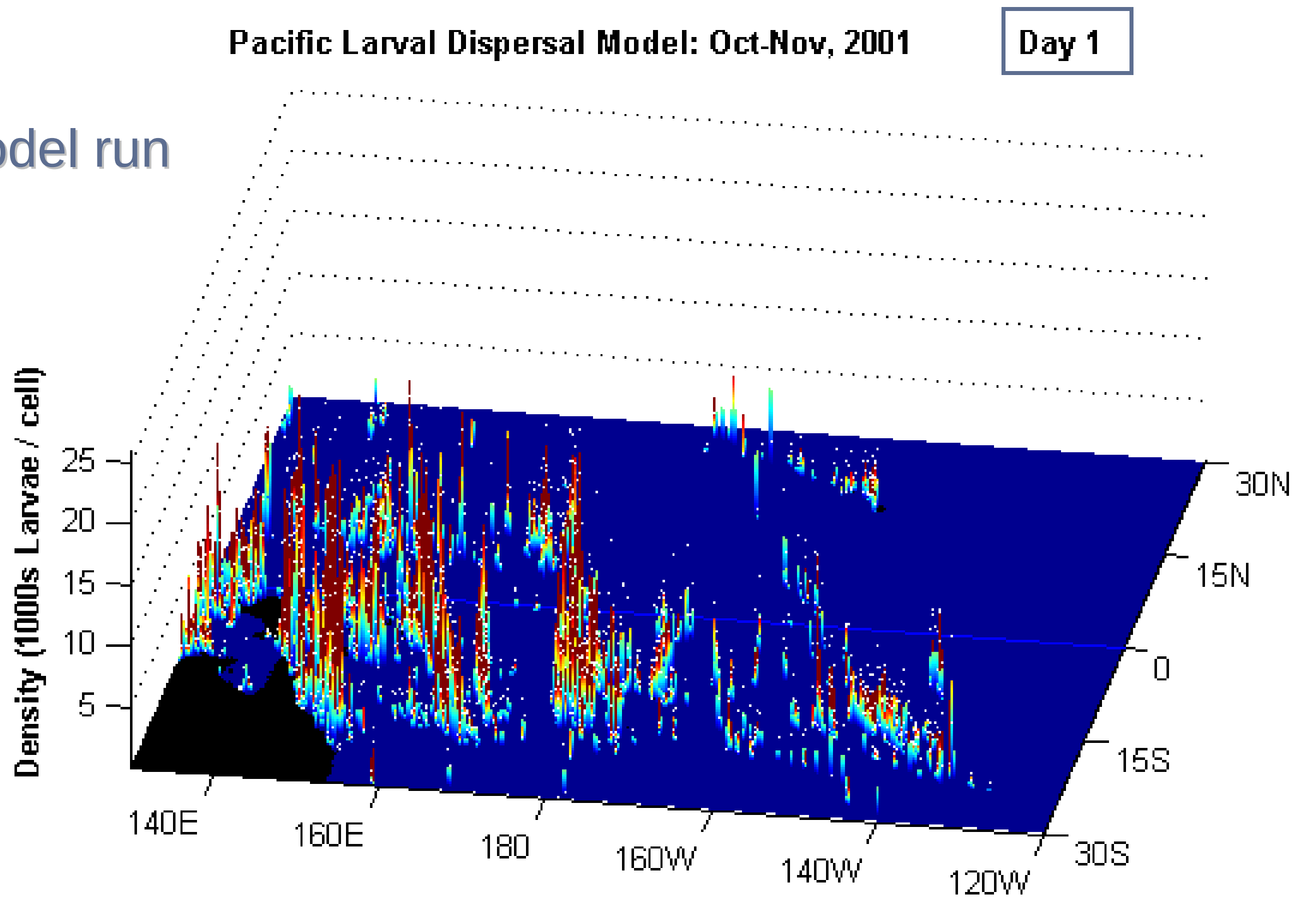
Marine Reserve Network Design

September 8, 2004

Larval dispersion simulation



42 day model run



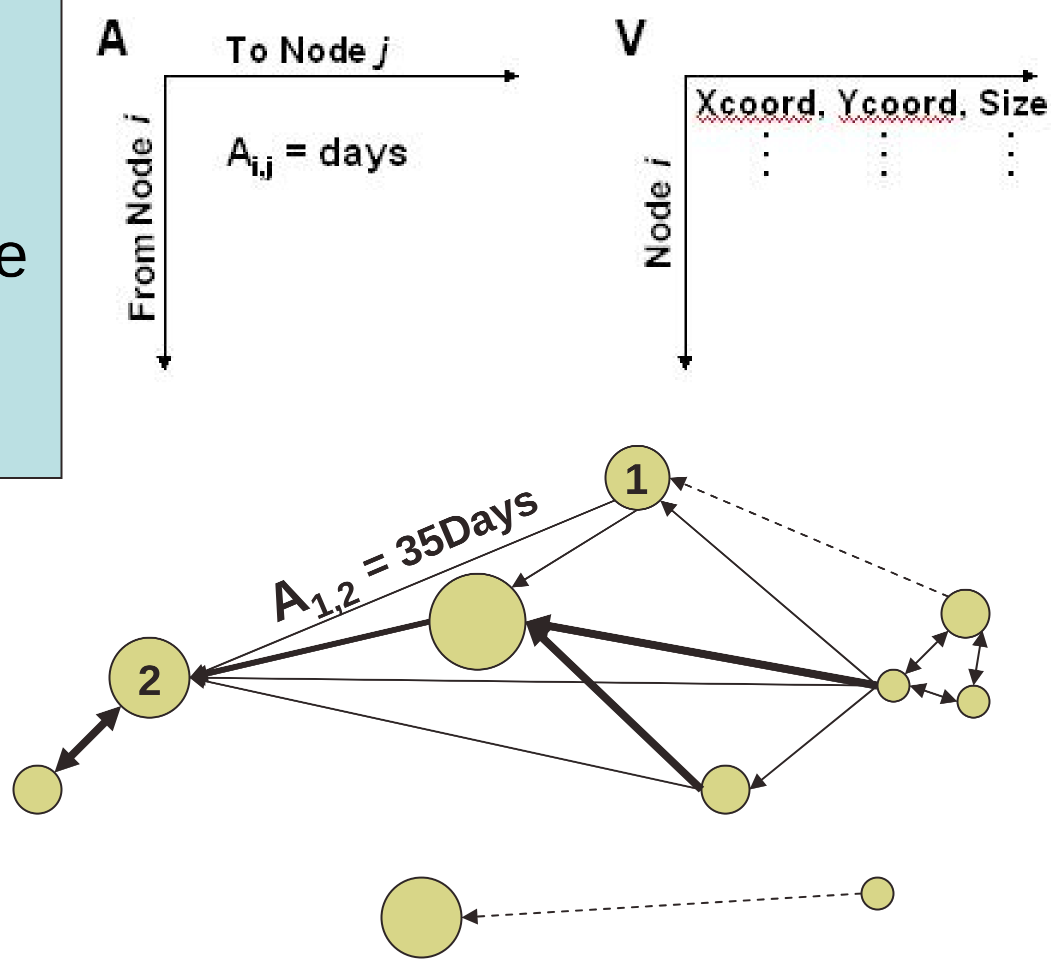
Methods

Network (Graph Theory) Framework

Structure: Adjacency Matrix [A], Vertices Matrix [V]

Tests

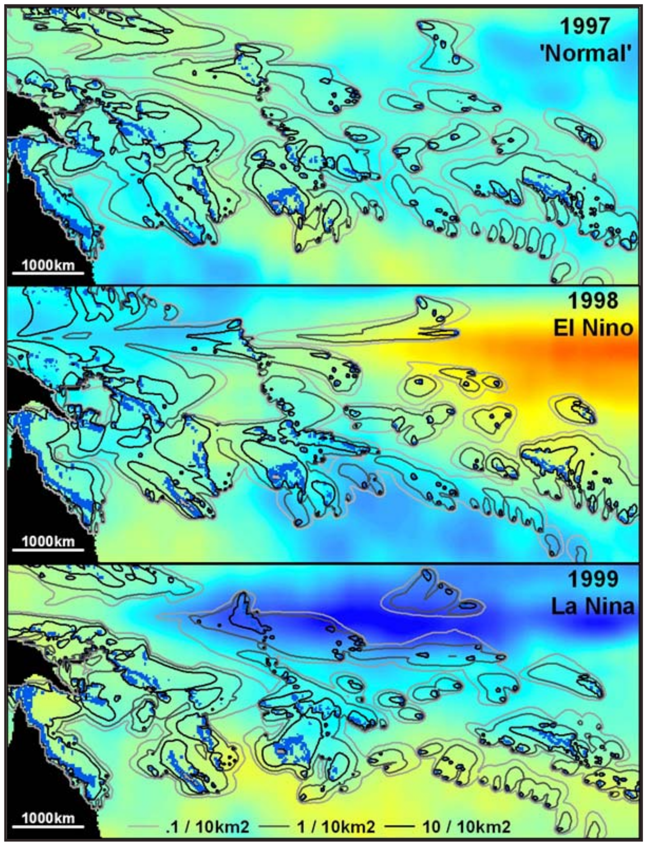
- ✓ $\boxed{\text{connectedness}}$
- ✓ upstream/downstream
- ✓ traverse time / distance
- ✓ node removal

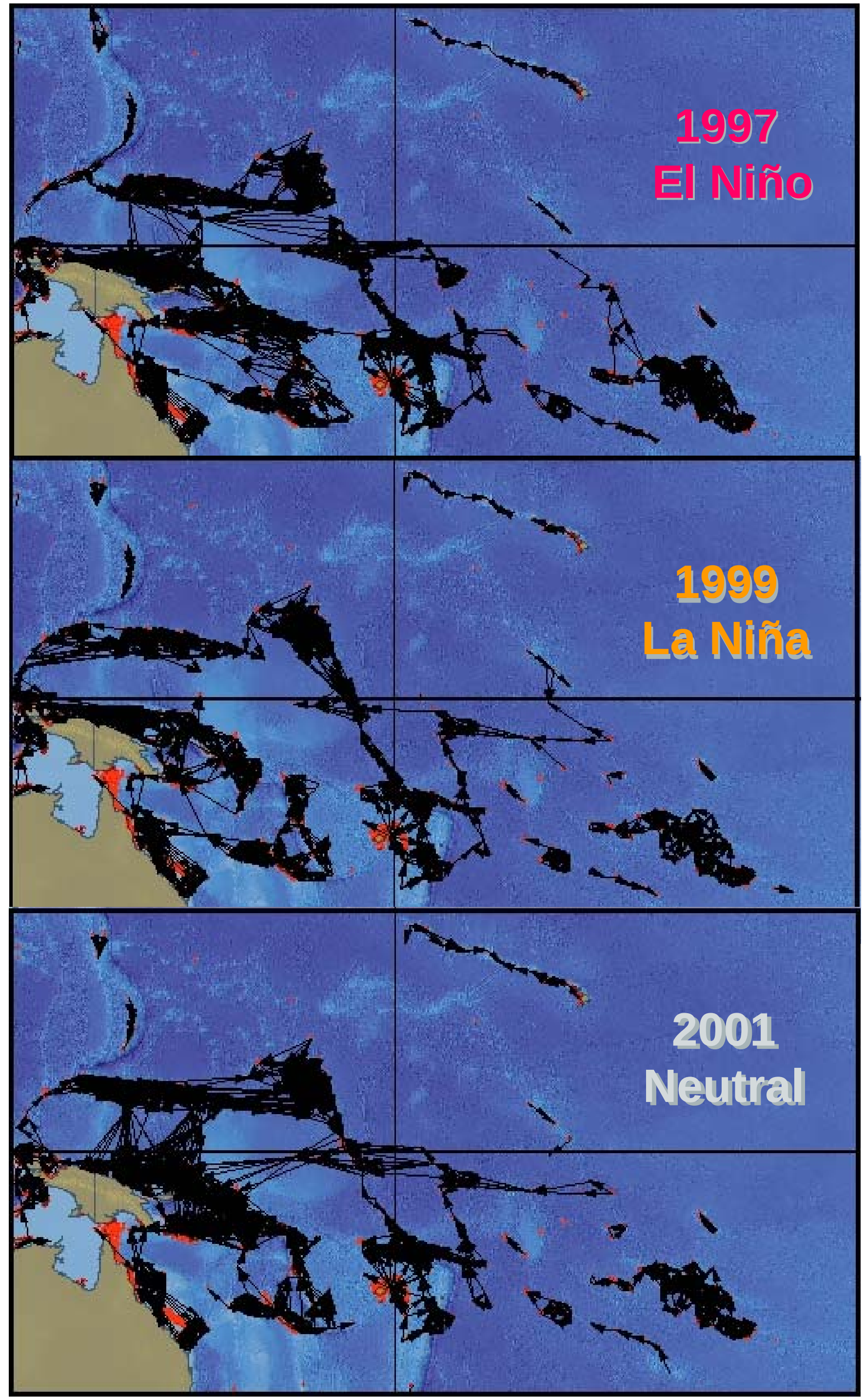


Results

Network Analysis

Yearly variability
w/45day threshold





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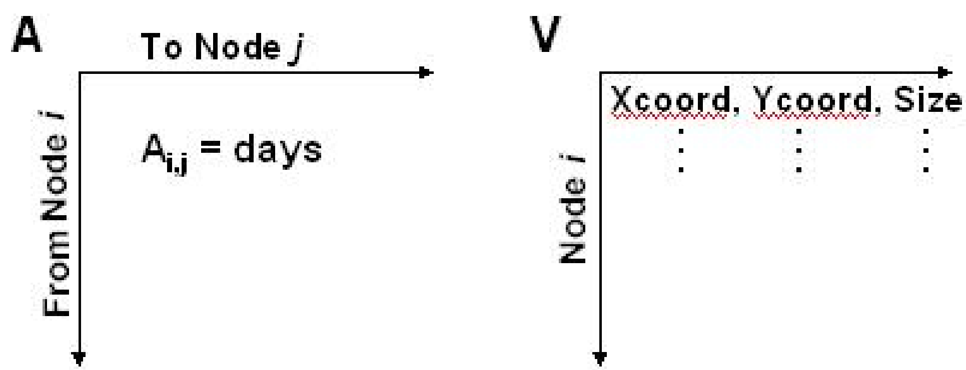
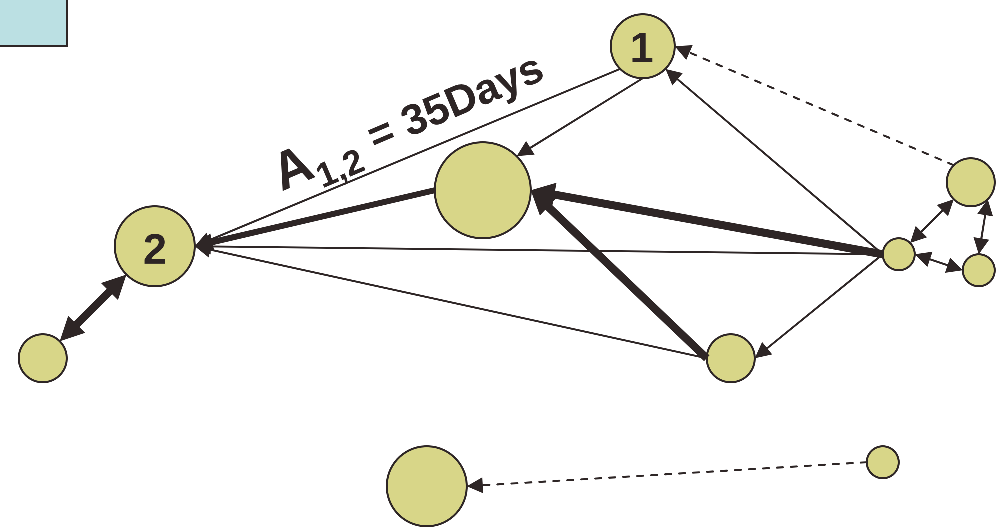
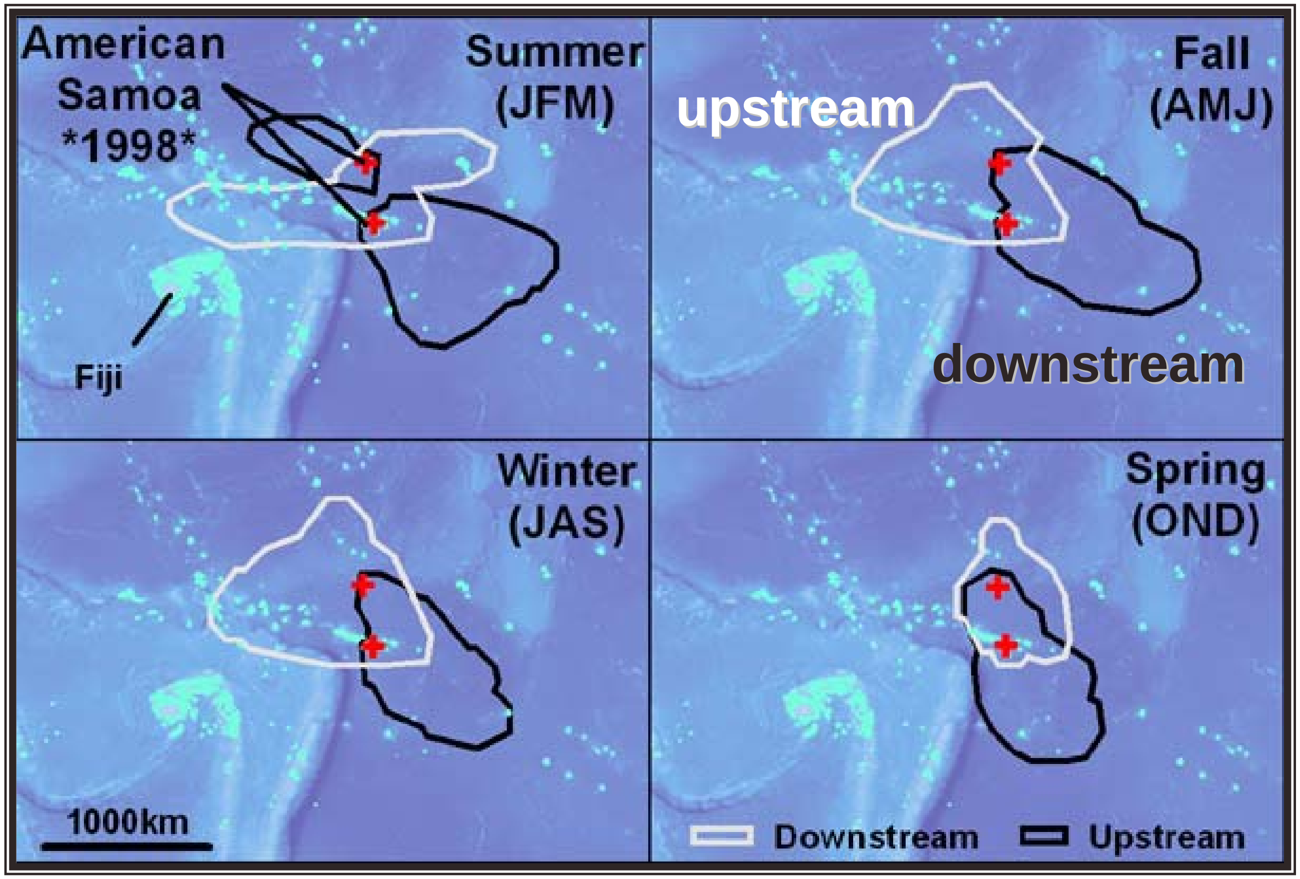




Preliminary Data: Results

American Samoa

- ✓ Few upstream larval sources
- ✓ Moderate seasonal variability
- ✓ Higher rate of retention?



Methods

Network (Graph Theory) Framework

Structure: Adjacency Matrix [A], Vertices Matrix [V]

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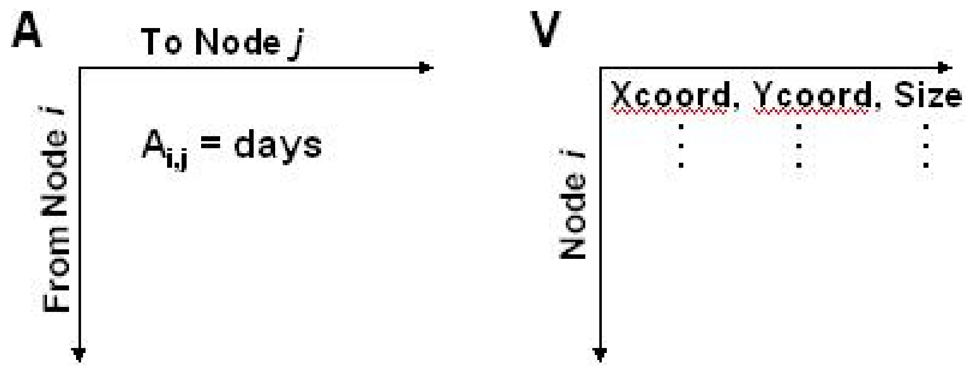
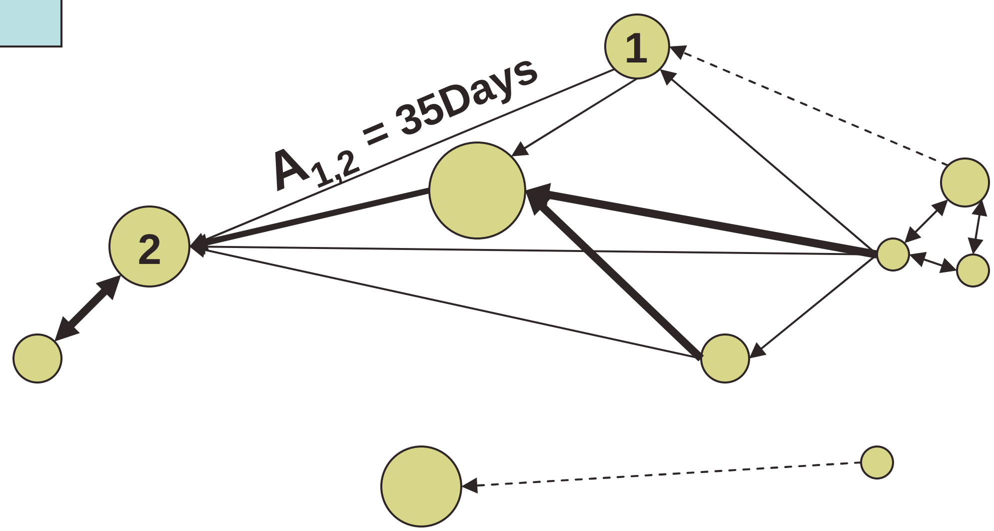




Results

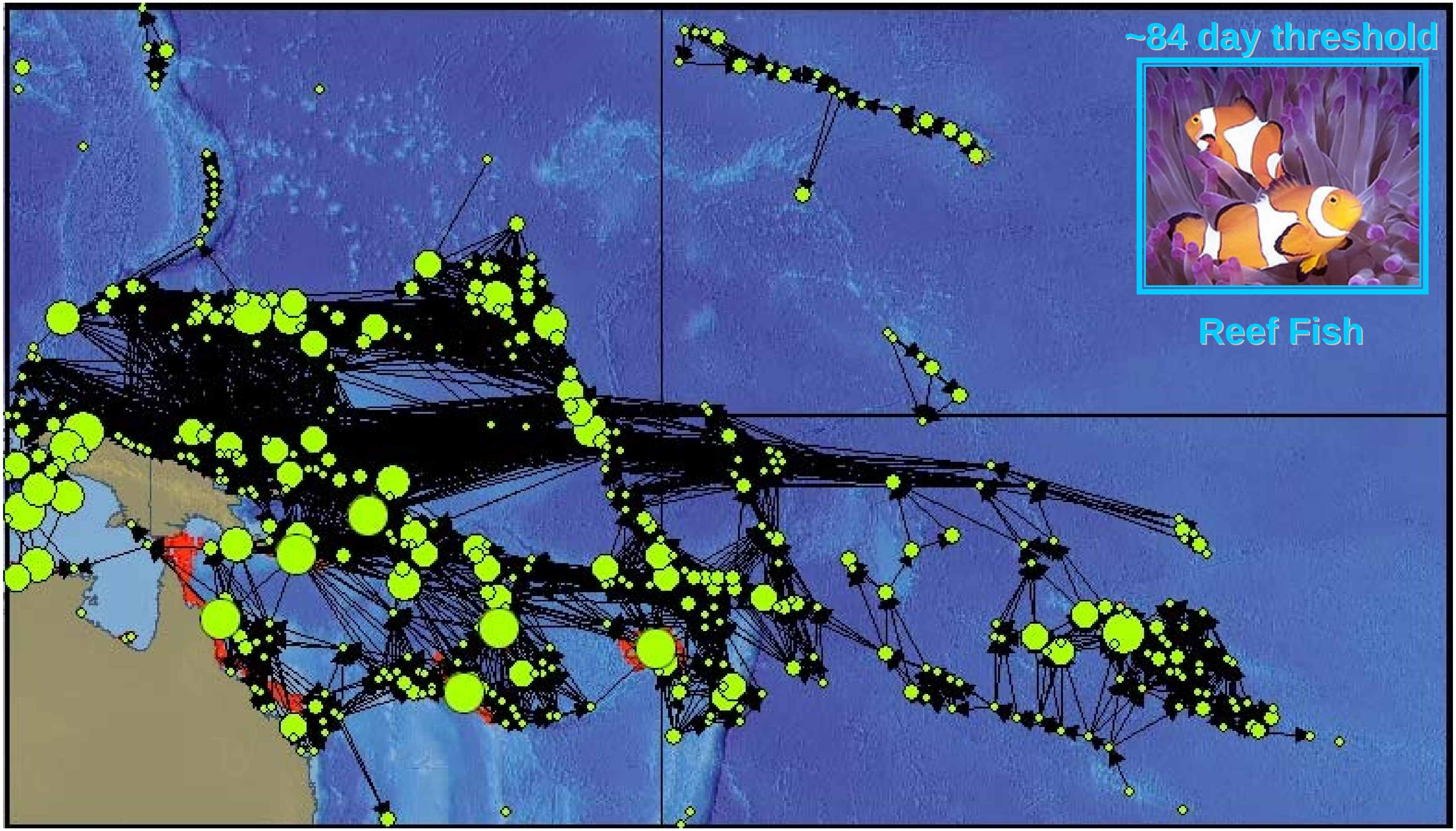
Network Analysis – Species' Dispersal Thresholds

84 days - fish
56 days - crustaceans
45 days - broadcasting corals
21 days - urchins and starfish (~14 – 28 day)
10 days - giant clam & sponge larvae

(very approximate times for representative species…)

Results

Network Analysis – Species' Dispersal Thresholds



Results

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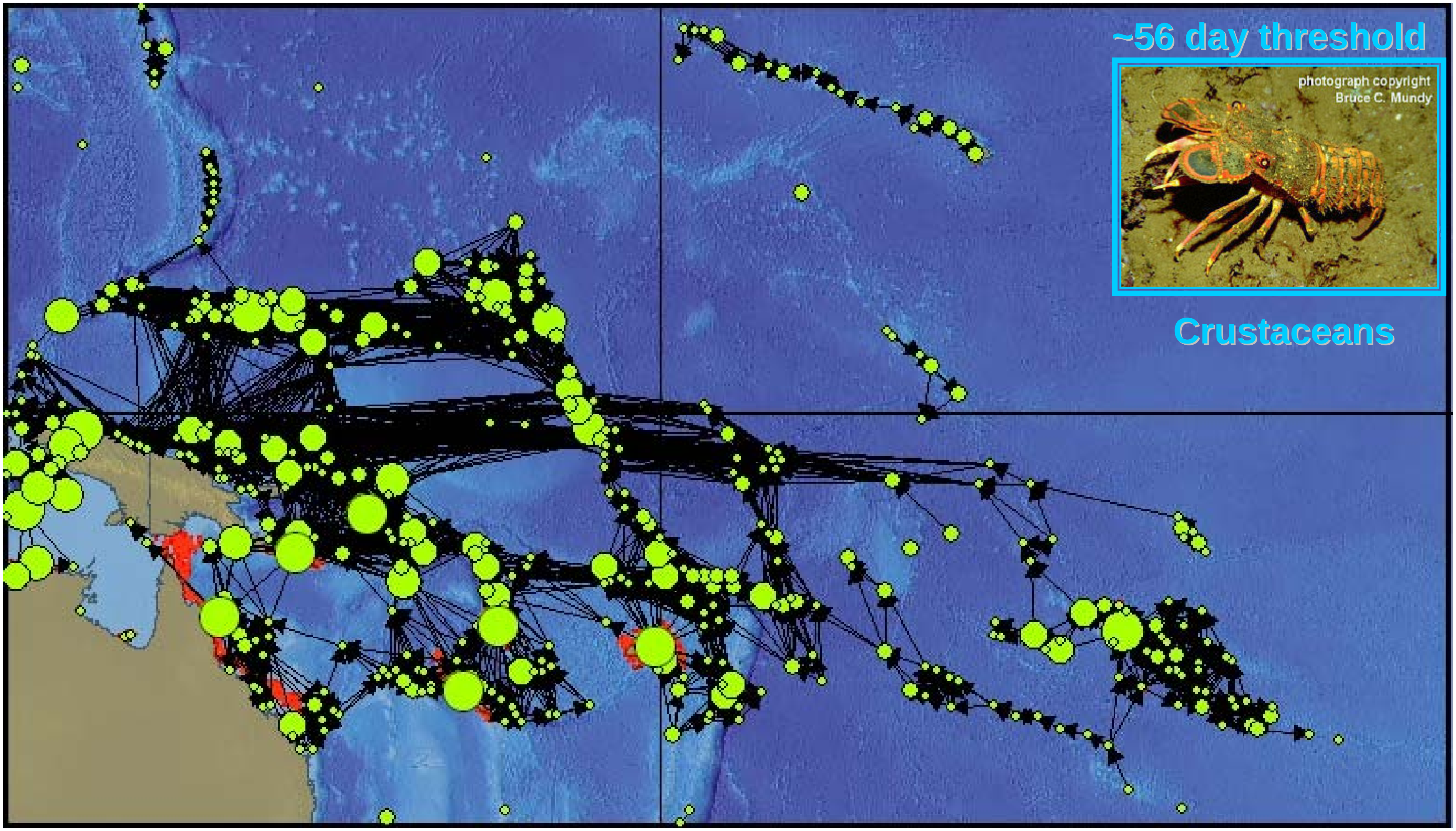

Results

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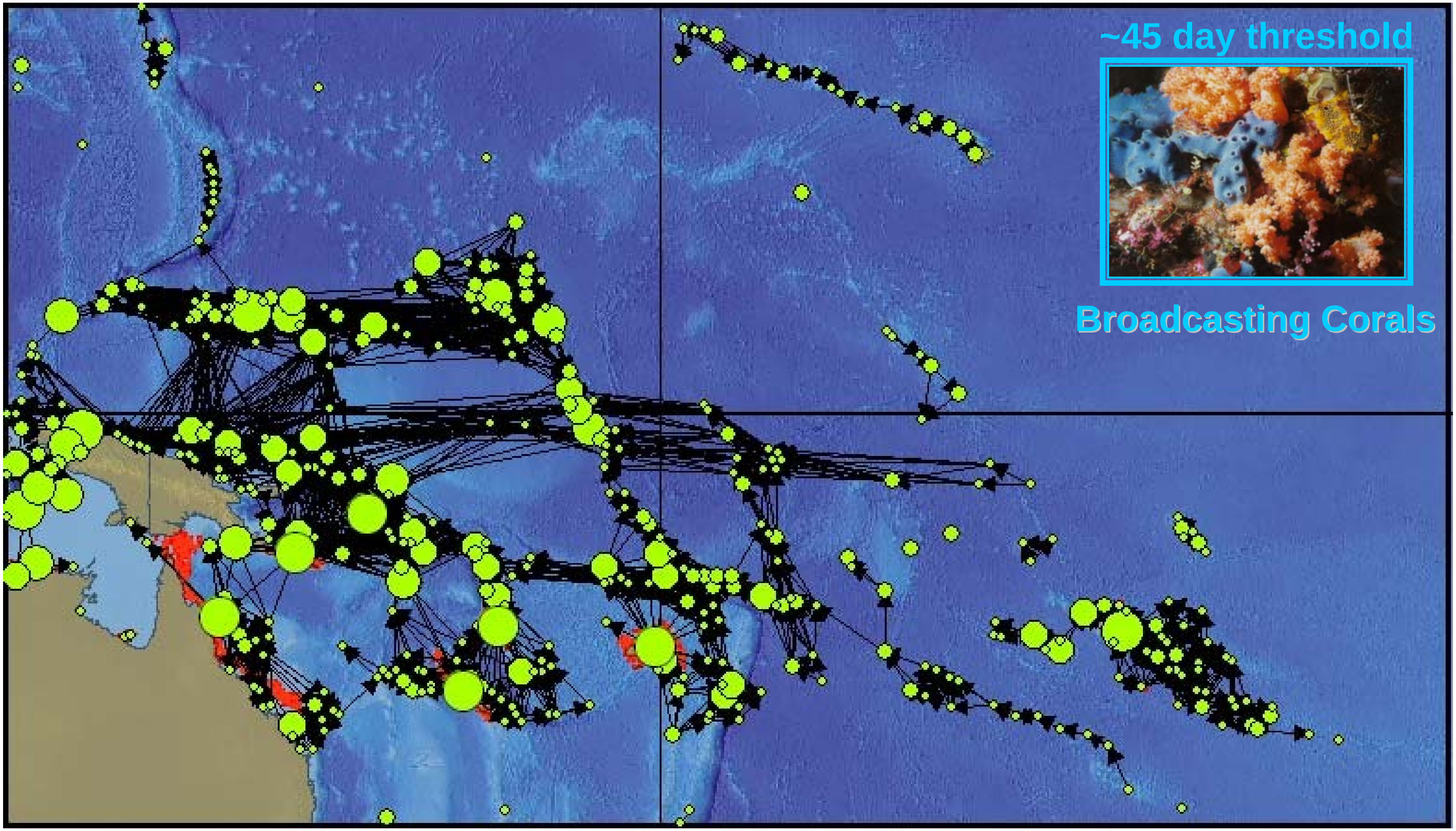
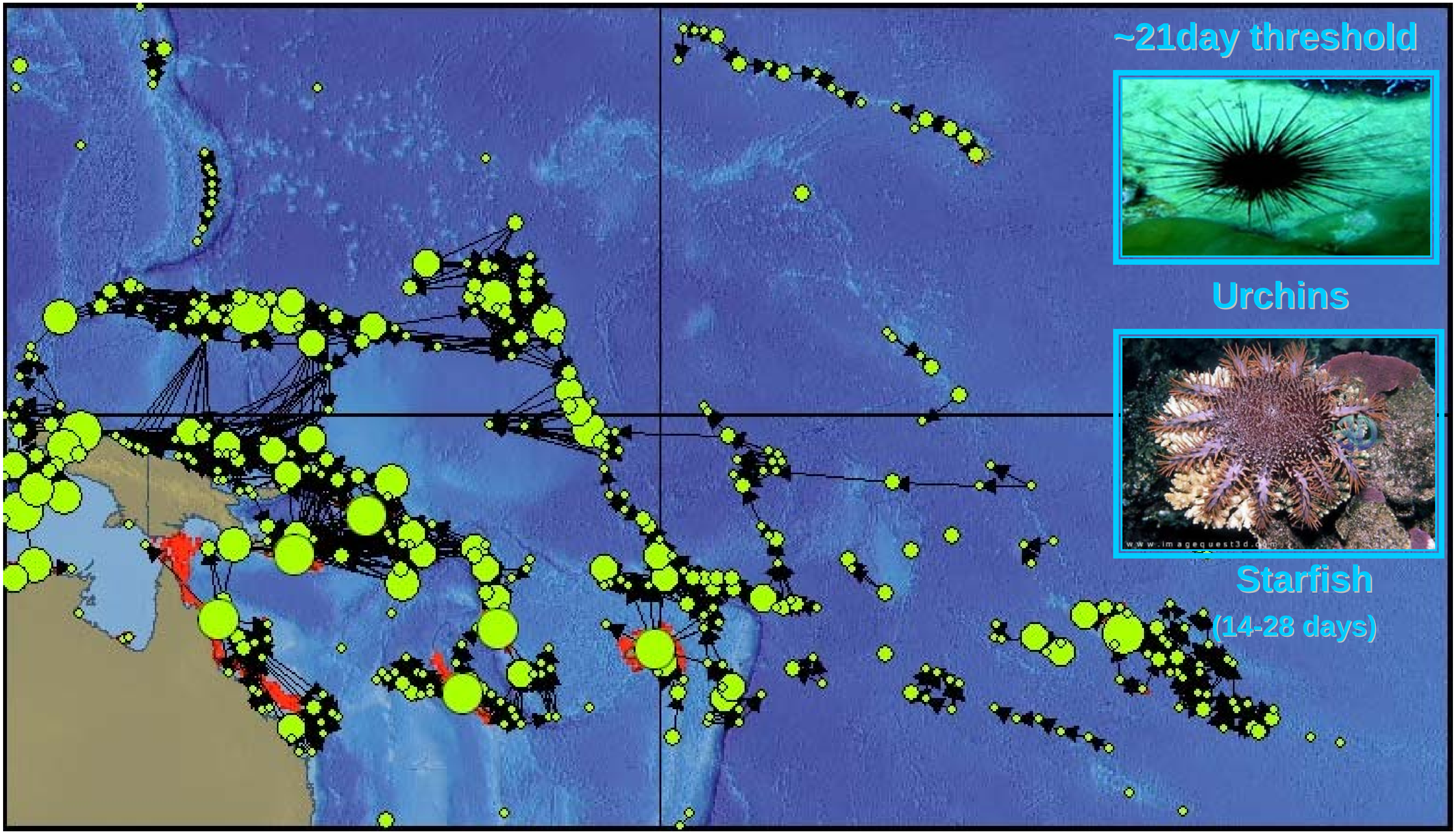


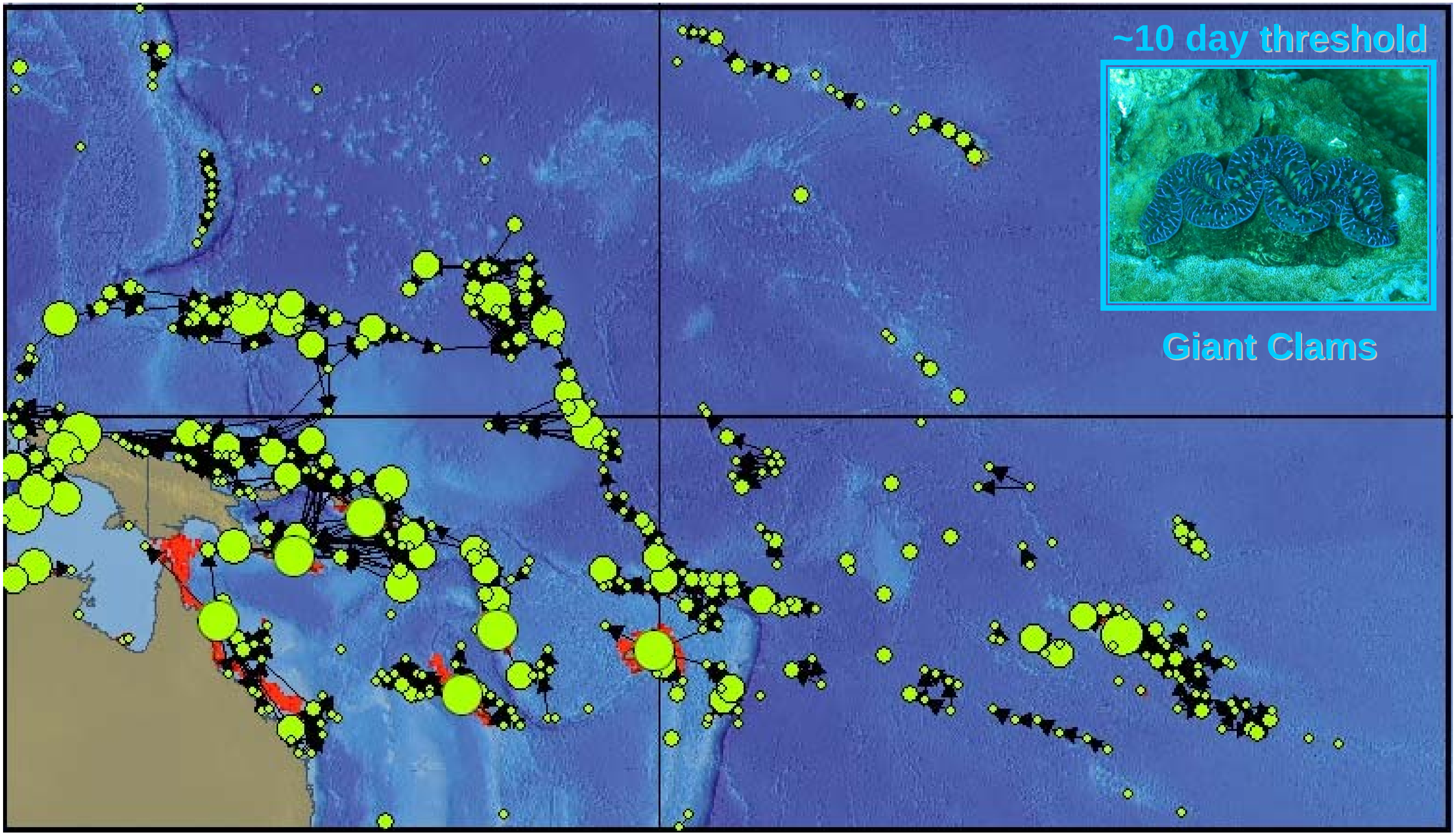
Results

Network Analysis – Species' Dispersal Thresholds



Results

Network Analysis – Species' Dispersal Thresholds



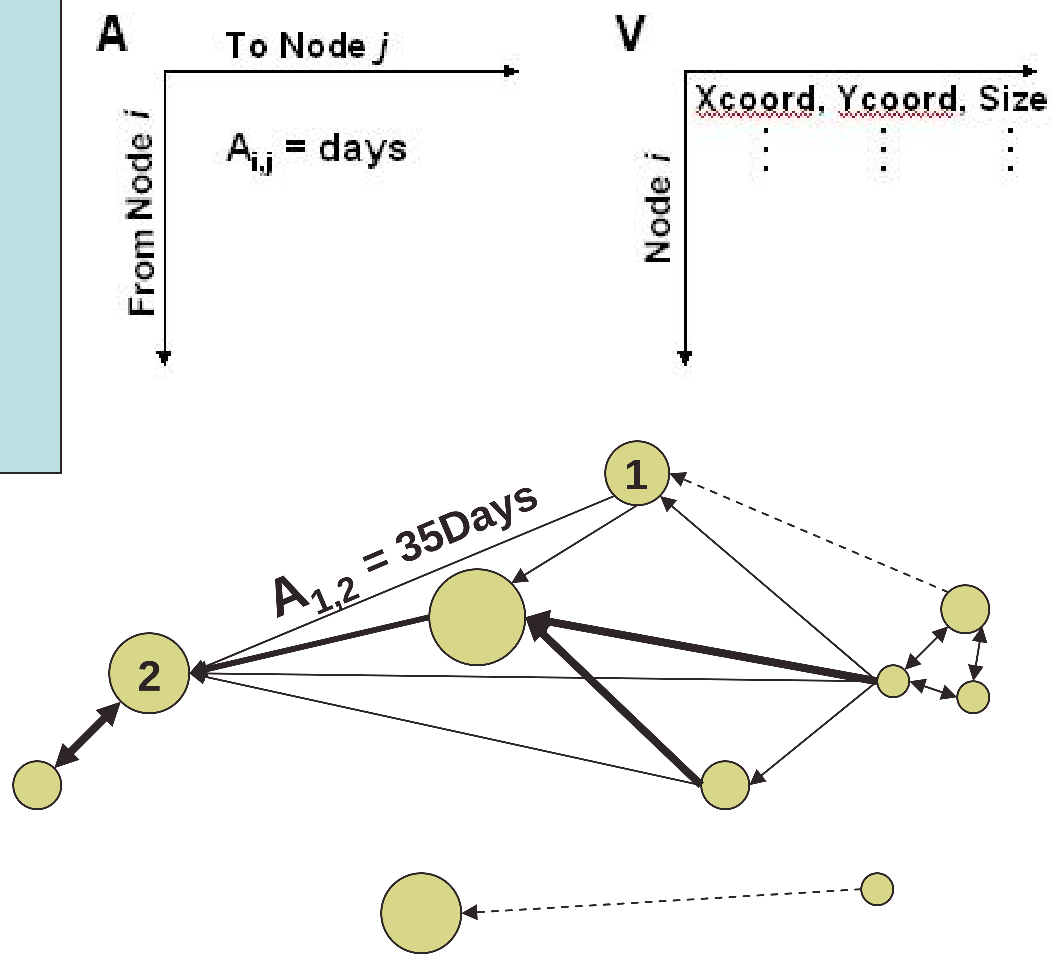
Methods

Network (Graph Theory) Framework

Structure: Adjacency Matrix [A], Vertices Matrix [V]

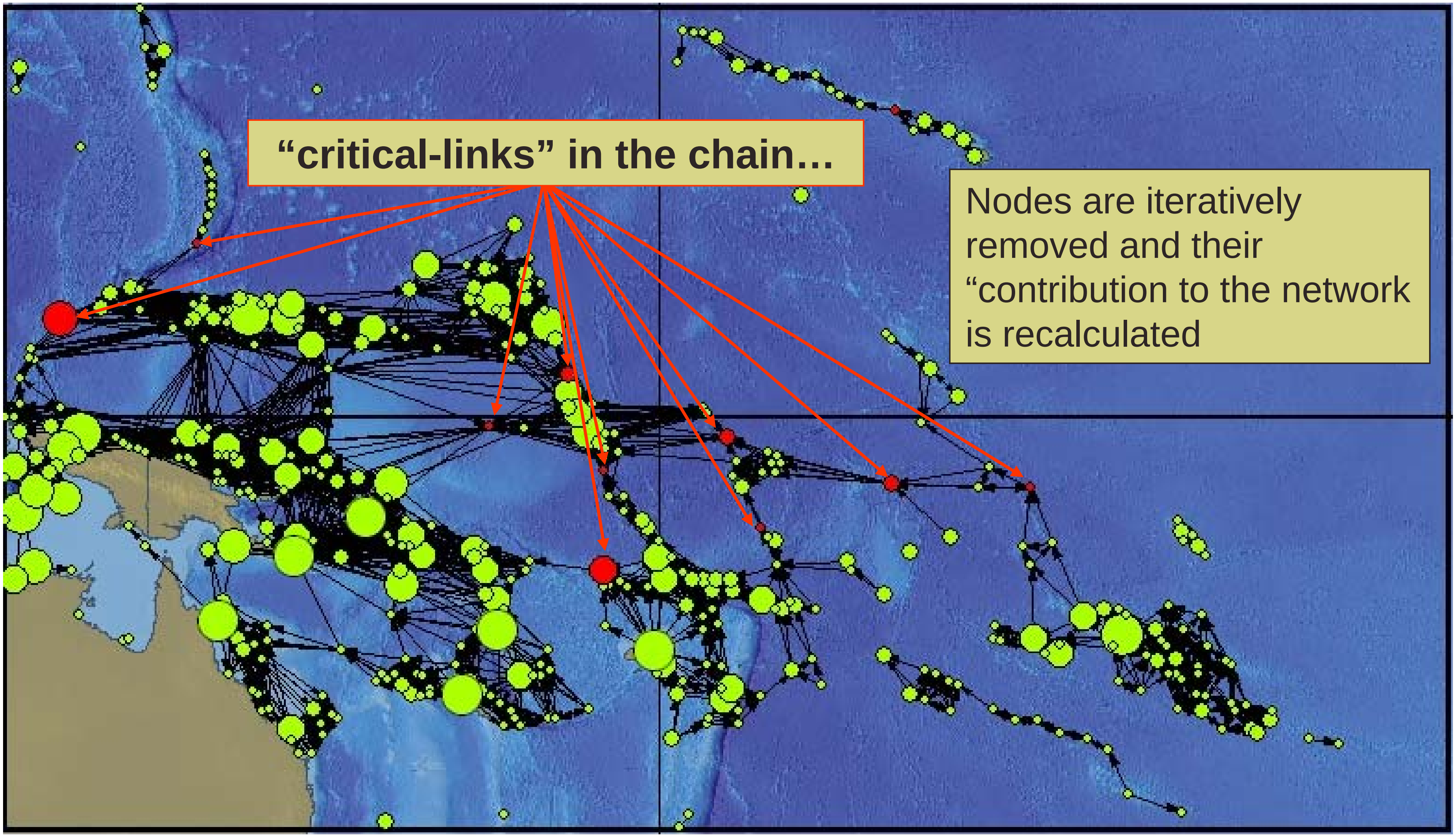
Tests

- ✓ connectedness
- ✓ shortest paths
- ✓ upstream/downstream
- ✓ node removal



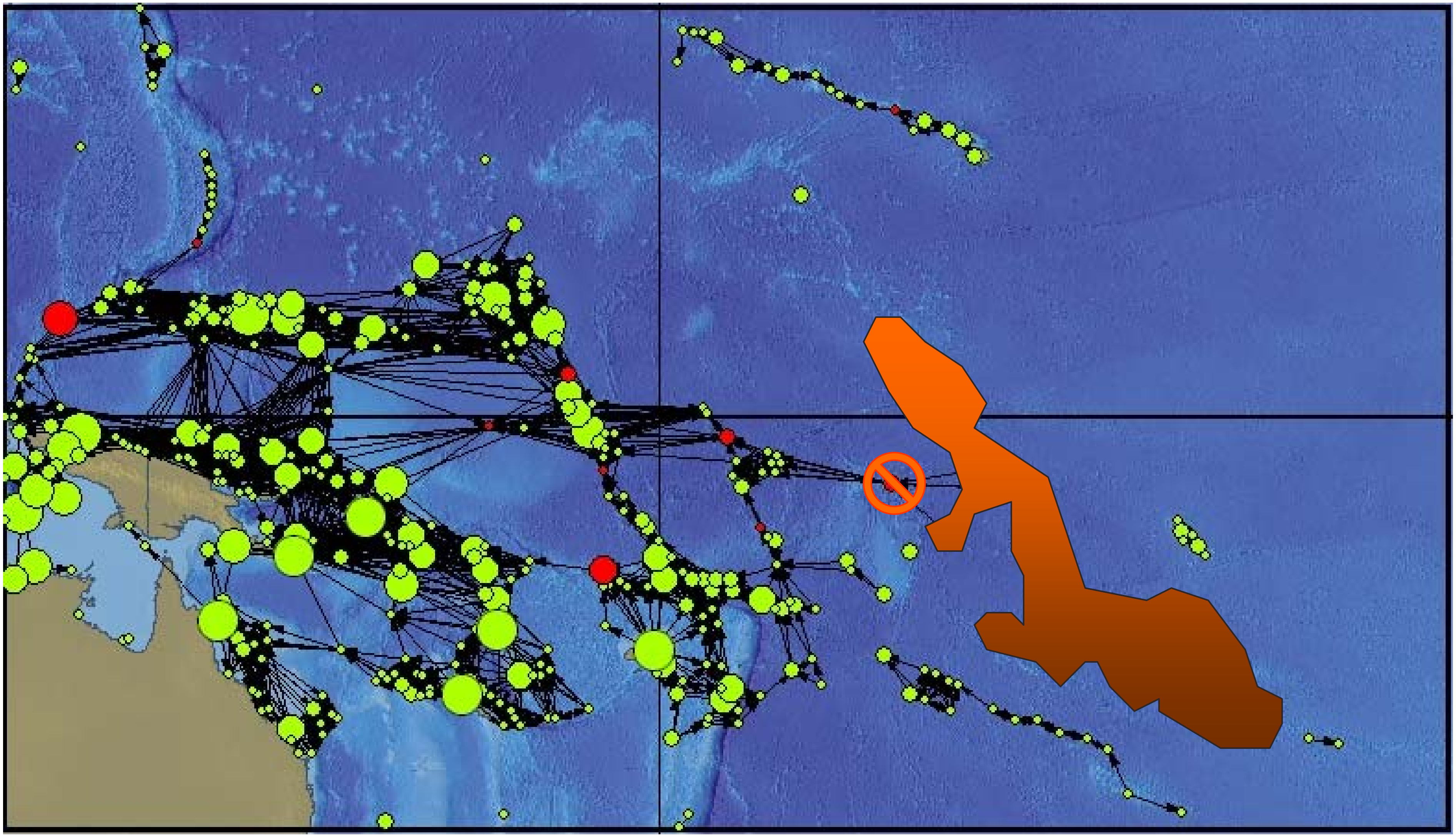
Results

Network Analysis – Key Stepping Stones (nodes)



Results

Network Analysis – Key Stepping Stones (nodes)



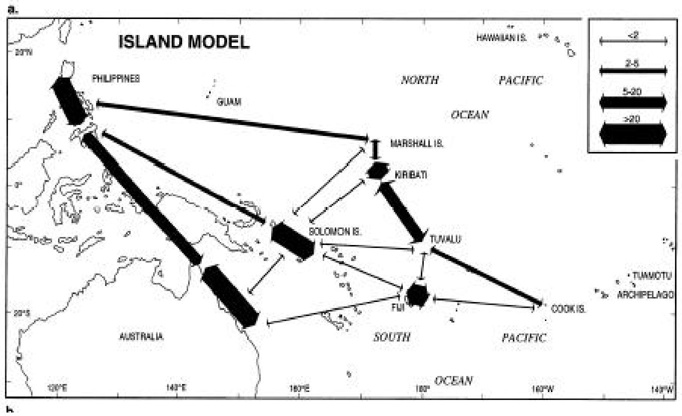
Future Work
Explore Relationships With Genetic Data

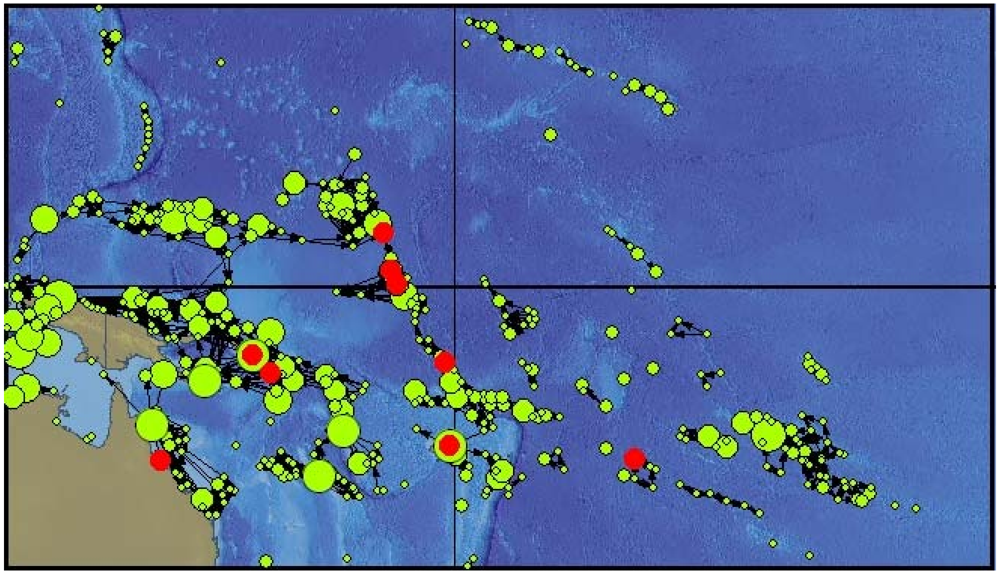
Phylogeography

+ Where is gene flow likely limited
+ Spatially explicit gene flow hypotheses
+ Test: genetic distance & network distance

Benzie & Williams, 1997

PATTERNS OF GENE FLOW IN *TRIDACNA MAXIMA*





Science needs

Marine connectivity analysis needs…

"Analyzing functional connectivity will require new spatio-temporal frameworks …

Needs:

- ✓ more objective, spatial analysis framework for connectivity analysis
- ✓ combination of hydrodynamics with ecosystem dynamics

Science needs

- ✓ **Background**

- ✓ **Habitat characterization**
  - ✓ Benthic “habitat”
  - ✓ Pelagic “habitat”

- ✓ **Spatio-temporal modeling**
  - ✓ Habitat modeling
  - ✓ Model evaluation
  - ✓ Spatio-temporal analysis

- ✓ **Connectivity analysis framework**

Questions?

NICHOLAS SCHOOL OF THE
ENVIRONMENT AND EARTH SCIENCES
DUKE UNIVERSITY